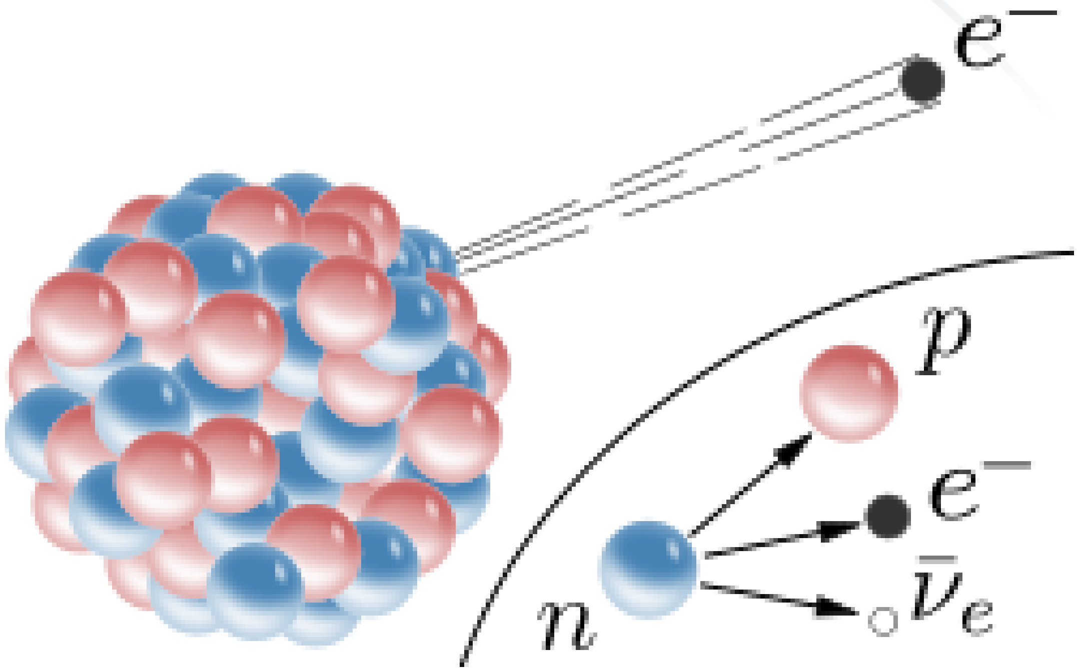
Neutron Beta Decay Measurements

Bryan Zeck

October 19th, 2016

UNCLASSIFIED

Beta Decay



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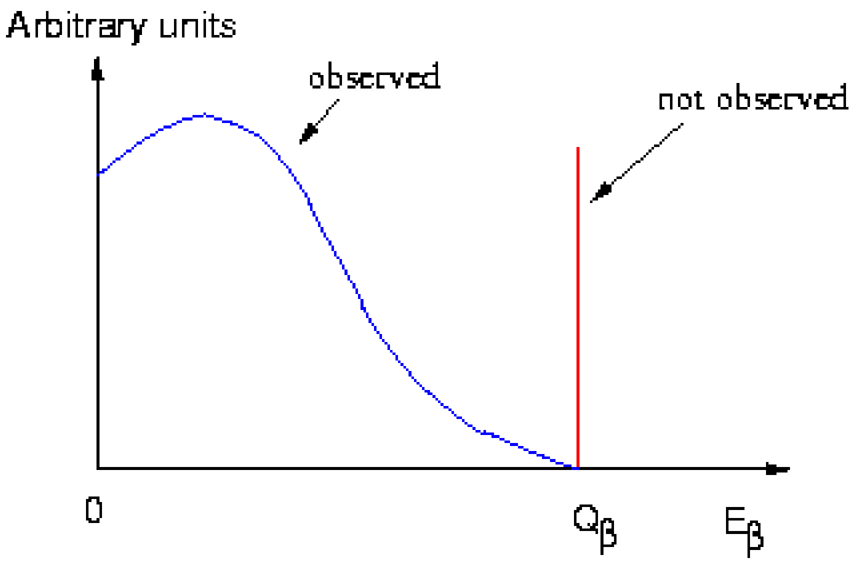
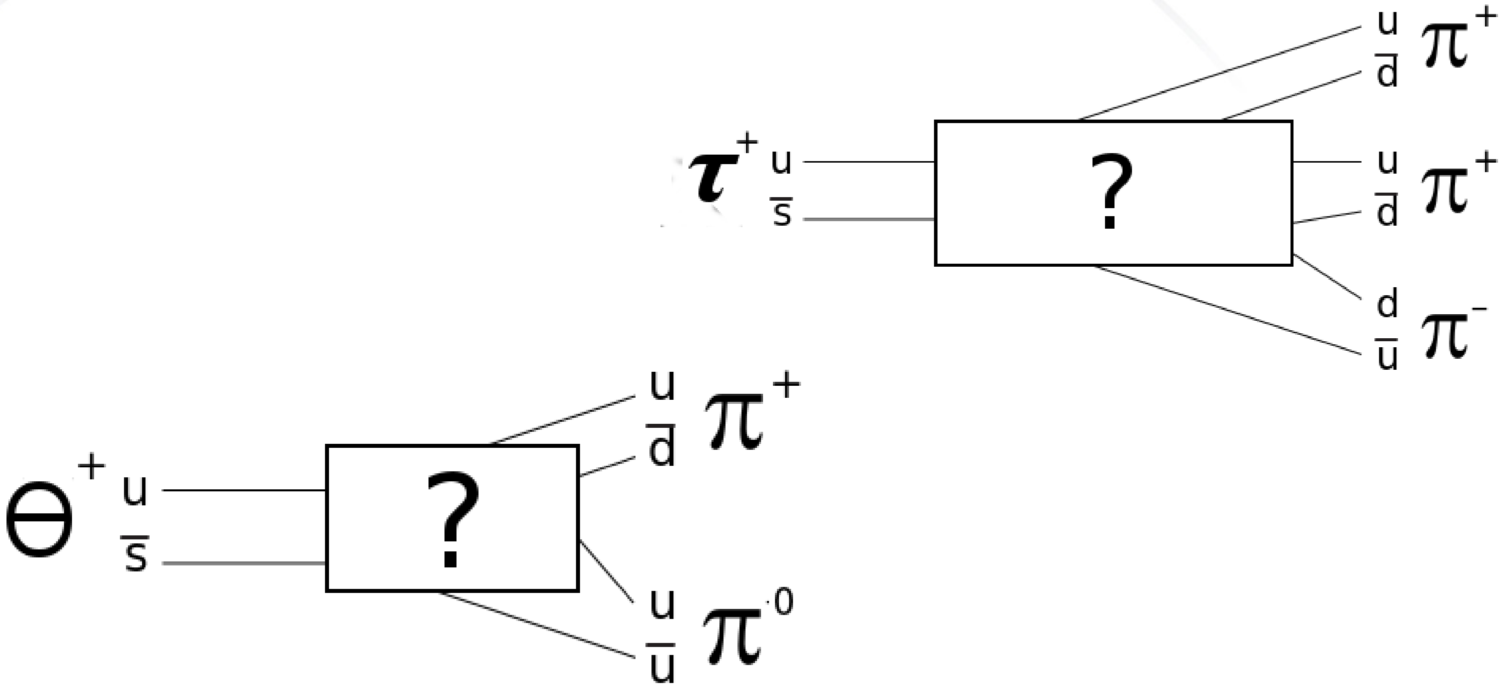
Beta Decay

- Rutherford: beta rays (1899)
- Becquerel: beta rays are electrons (1900)
- Fermi: Theory for beta decay (1934)



Pauli proposed neutrino to account for observed beta decay spectrum (1930)

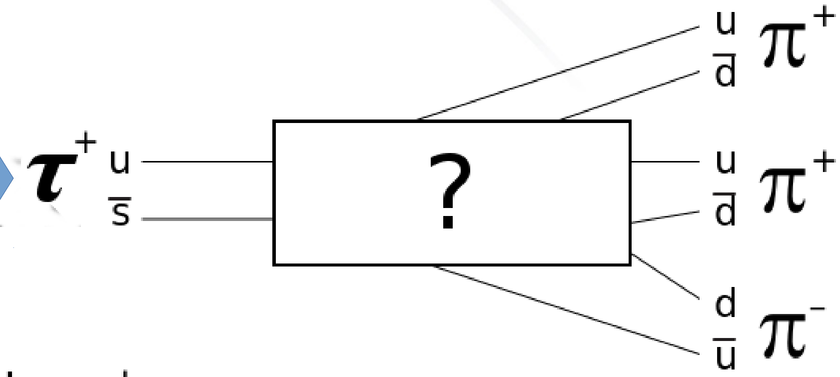
The τ-θ Puzzle

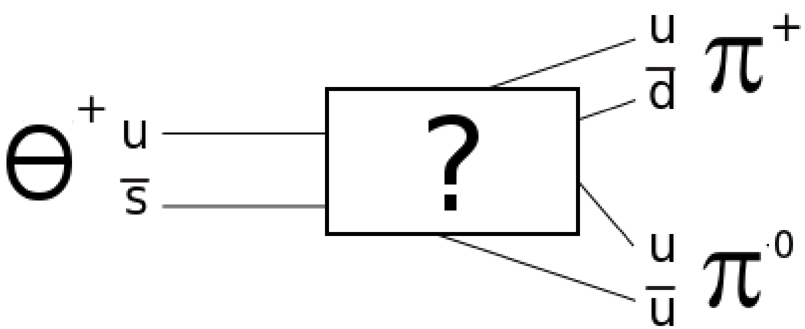


The τ-θ Puzzle

$m_\tau = 966.3 \pm 2.1\ m_e$

$\lambda_\tau = 1.0_{-0.3}^{+0.7} \times 10^{-8}\ s$

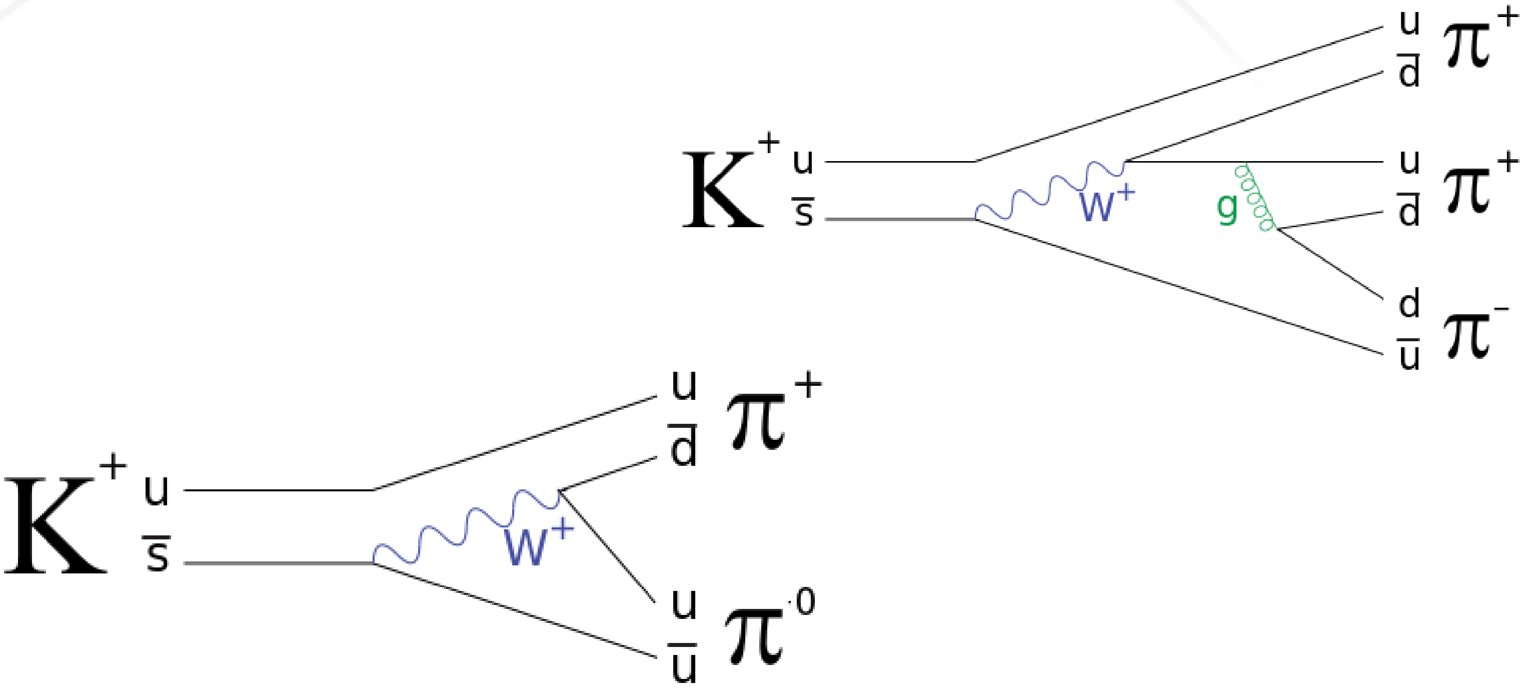




$m_\Theta = 966.7 \pm 2.0\ m_e$

$\lambda_\Theta = 1.3 \pm 0.2 \times 10^{-8}\ s$

The τ-θ Puzzle



Lee and Yang

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

One way out of the difficulty is to assume that parity is not strictly conserved, so that θ^+ and τ^+ are two different decay modes of the same particle, which necessarily has a single mass value and a single lifetime.

If parity is not conserved in β decay, the most general form of Hamiltonian can be written as

$$\begin{aligned} H_{\text{int}} = {} & (\psi_p^\dagger\gamma_4\psi_n)(C_S\psi_e^\dagger\gamma_4\psi_\nu + C_S'\psi_e^\dagger\gamma_4\gamma_5\psi_\nu) \\ & + (\psi_p^\dagger\gamma_4\gamma_\mu\psi_n)(C_V\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu + C_V'\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu) \\ & + \tfrac{1}{2}(\psi_p^\dagger\gamma_4\sigma_{\lambda\mu}\psi_n)(C_T\psi_e^\dagger\gamma_4\sigma_{\lambda\mu}\psi_\nu \\ & + C_T'\psi_e^\dagger\gamma_4\sigma_{\lambda\mu}\gamma_5\psi_\nu) + (\psi_p^\dagger\gamma_4\gamma_\mu\gamma_5\psi_n) \\ & \times(-C_A\psi_e^\dagger\gamma_4\gamma_\mu\gamma_5\psi_\nu - C_A'\psi_e^\dagger\gamma_4\gamma_\mu\psi_\nu) \\ & + (\psi_p^\dagger\gamma_4\gamma_5\psi_n)(C_P\psi_e^\dagger\gamma_4\gamma_5\psi_\nu + C_P'\psi_e^\dagger\gamma_4\psi_\nu), \end{aligned} \quad \text{(A.1)}$$

where $\sigma_{\lambda\mu} = -\frac{1}{2}i(\gamma_\lambda\gamma_\mu - \gamma_\mu\gamma_\lambda)$ and $\gamma_5 = \gamma_1\gamma_2\gamma_3\gamma_4$. The

Jackson, Treiman, and Wyld

Possible Tests of Time Reversal Invariance in Beta Decay

J. D. JACKSON,* S. B. TREIMAN, AND H. W. WYLD, JR.
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

(Received January 28, 1957)

lines have now been carried out. Wu, Ambler, Hayward, Hoppes, and Hudson[4] in fact find a large asymmetry effect in the beta decay of Co^{60}. In addition to this,

measured. There are four vector quantities which conceivably could be measured in a beta-decay experiment: $\langle \mathbf{J} \rangle$, the polarization of the decaying nucleus; $\boldsymbol{\sigma}$, the polarization direction of the electron; $\mathbf{p}_e$, the electron momentum; and $\mathbf{p}_\nu$, the neutrino momentum. Since all four of these vectors change sign under time reversal, the scalar triple product of any three of them gives a term invariant under rotations but noninvariant under time reversal. Hence the detection of such a term in a beta-decay experiment would indicate noninvariance under time reversal.[6a]

Jackson, Treiman, and Wyld

II. RECOIL EXPERIMENTS WITH ORIENTED NUCLEI

$$\omega(\langle J\rangle|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu$$
$$=\frac{1}{(2\pi)^5}p_e E_e(E^0-E_e)^2 dE_e d\Omega_e d\Omega_\nu \xi\Bigg\{1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+b\frac{m}{E_e}$$
$$+c\left[\frac{1}{3}\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}-\frac{(\mathbf{p}_e\cdot\mathbf{j})(\mathbf{p}_\nu\cdot\mathbf{j})}{E_eE_\nu}\right]\left[\frac{J(J+1)-3\langle(\mathbf{J}\cdot\mathbf{j})^2\rangle}{J(2J-1)}\right]$$
$$+\frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e}+B\frac{\mathbf{p}_\nu}{E_\nu}+D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]\Bigg\}. \quad (2)$$

III. ELECTRON POLARIZATION IN RECOIL EXPERIMENT

$$\omega(\boldsymbol{\sigma}|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu$$
$$=\frac{1}{(2\pi)^5}p_e E_e(E^0-E_e)^2 dE_e d\Omega_e d\Omega_\nu$$
$$\times\tfrac{1}{2}\xi\Bigg\{1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+b\frac{m}{E_e}+\boldsymbol{\sigma}\cdot\Bigg[G\frac{\mathbf{p}_e}{E_e}+H\frac{\mathbf{p}_\nu}{E_\nu}$$
$$+K\frac{\mathbf{p}_e}{E_e+m}\left(\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}\right)+L\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\Bigg]\Bigg\}. \quad (3)$$

IV. ELECTRON POLARIZATION IN DECAY OF ORIENTED NUCLEI

$$\omega(\langle\mathbf{J}\rangle,\boldsymbol{\sigma}|E_e,\Omega_e)dE_e d\Omega_e$$
$$=\frac{1}{(2\pi)^4}p_e E_e(E^0-E_e)^2 dE_e d\Omega_e$$
$$\times\xi\Bigg\{1+b\frac{m}{E_e}+\left(A\frac{\langle\mathbf{J}\rangle}{J}+G\boldsymbol{\sigma}\right)\cdot\frac{\mathbf{p}_e}{E_e}+\boldsymbol{\sigma}\cdot\Bigg[N\frac{\langle\mathbf{J}\rangle}{J}$$
$$+Q\frac{\mathbf{p}_e}{E_e+m}\left(\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}_e}{E_e}\right)+R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}_e}{E_e}\Bigg]\Bigg\}. \quad (6)$$

Jackson, Treiman, and Wyld

II. RECOIL EXPERIMENTS WITH ORIENTED NUCLEI

$$\omega(\langle J\rangle|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu$$
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$$+c\left[\frac{1}{3}\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}-\frac{(\mathbf{p}_e\cdot\mathbf{j})(\mathbf{p}_\nu\cdot\mathbf{j})}{E_eE_\nu}\right]\left[\frac{J(J+1)-3\langle(\mathbf{J}\cdot\mathbf{j})^2\rangle}{J(2J-1)}\right]$$
$$+\frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e}+B\frac{\mathbf{p}_\nu}{E_\nu}+D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]\bigg\}. \quad (2)$$

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$$\times\tfrac{1}{2}\xi\bigg\{1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+b\frac{m}{E_e}+\boldsymbol{\sigma}\cdot\bigg[G\frac{\mathbf{p}_e}{E_e}+H\frac{\mathbf{p}_\nu}{E_\nu}$$
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IV. ELECTRON POLARIZATION IN DECAY OF ORIENTED NUCLEI

$$\omega(\langle\mathbf{J}\rangle,\boldsymbol{\sigma}|E_e,\Omega_e)dE_ed\Omega_e$$
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$$\times\xi\bigg\{1+b\frac{m}{E_e}+\left(A\frac{\langle\mathbf{J}\rangle}{J}+G\boldsymbol{\sigma}\right)\cdot\frac{\mathbf{p}_e}{E_e}+\boldsymbol{\sigma}\cdot\bigg[N\frac{\langle\mathbf{J}\rangle}{J}$$
$$+Q\frac{\mathbf{p}_e}{E_e+m}\left(\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}_e}{E_e}\right)+R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}_e}{E_e}\bigg]\bigg\}. \quad (6)$$

Form of the Weak Interaction

Scalar	$H_{\mathrm{int}} = (\bar{\psi}_p \psi_n)(C_S \bar{\psi}_e \psi_\nu + C_S' \bar{\psi}_e \gamma_5 \psi_\nu)$
Vector	$+ (\bar{\psi}_p \gamma_\mu \psi_n)(C_V \bar{\psi}_e \gamma_\mu \psi_\nu + C_V' \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu)$
Tensor	$+ \frac{1}{2} (\bar{\psi}_p \sigma_{\lambda\mu} \psi_n)(C_T \bar{\psi}_e \sigma_{\lambda\mu} \psi_\nu + C_T' \bar{\psi}_e \sigma_{\lambda\mu} \gamma_5 \psi_\nu)$
Axial Vector	$- (\bar{\psi}_p \gamma_\mu \gamma_5 \psi_n)(C_A \bar{\psi}_e \gamma_\mu \gamma_5 \psi_\nu + C_A' \bar{\psi}_e \gamma_\mu \psi_\nu)$
Pseudoscalar	$+ (\bar{\psi}_p \gamma_5 \psi_n)(C_P \bar{\psi}_e \gamma_5 \psi_\nu + C_P' \bar{\psi}_e \psi_\nu)$
	$+ \text{Hermitian conjugate}$

How to pare this down?

In beta decay, pseudoscalar interaction is negligible

Fermi: S, V   Gamow-Teller: T, A

Unpolarized Beta Decay Spectra

Note that all of the couplings give a similar form for $|\mathcal{M}|^2$, namely

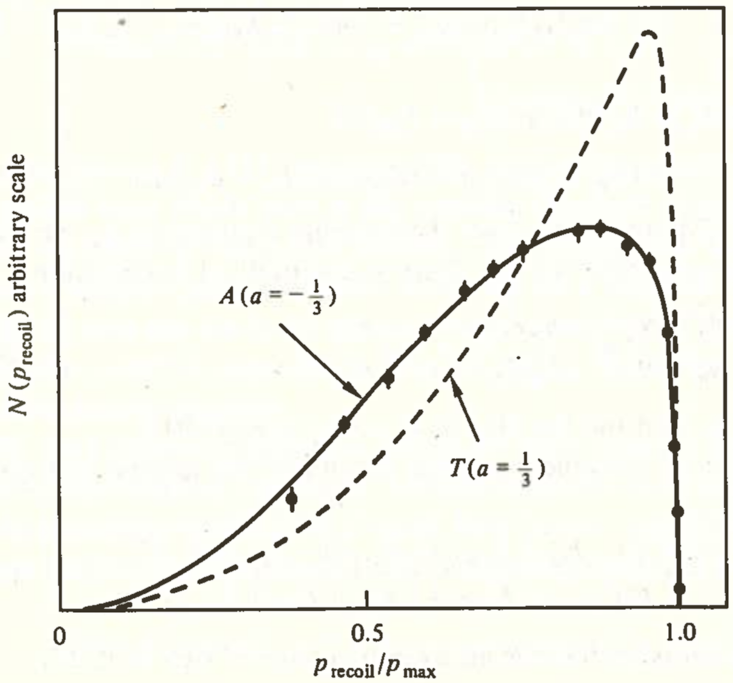
$$|\mathcal{M}_i|^2 = 4K_i E_3 E_4 (1 + a_i \beta \cos\theta), \tag{5.12}$$

with $K_i = |\langle r \rangle|^2 (|C_i|^2 + |C_i'|^2)$, where $r = 1$ or σ as appropriate, and with

$$a_S = -1, \qquad a_V = 1, \qquad a_T = \tfrac{1}{3}, \qquad a_A = -\tfrac{1}{3}, \tag{5.13}$$

The coefficient a in (5.13) and (5.20) is also sensitive to the type of coupling. Experimentally, the values found are consistent with V and A couplings only. For example, Allen *et al*. (1959) measure $a = 0.97 \pm 0.14$ for $^{35}Ar \rightarrow {}^{35}Cl\, e^+ \nu_e$ (pure F), whereas, for the pure GT decay $^6He \rightarrow {}^6Li\, e^- \bar{\nu}_e$, Johnson *et al*. (1963) give $a = -0.3343 \pm 0.0030$. Note that for pure F or

Fig 5.2 Recoil momentum spectrum for the decay $^6He \rightarrow Li\, e^- \bar{\nu}_e$, together with the predictions for pure A and pure T couplings. (1)



(1) Renton, P. 1990. Electroweak Interactions. Campbriddge University Press.

Cobalt-60

Los Alamos
NATIONAL LABORATORY
EST. 1943

Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson,
National Bureau of Standards, Washington, D. C.

(Received January 15, 1957)

(2)

along the axis. The results showed that the electrons were emitted preferentially in the direction opposite to that of nuclear spin and therefore conclusively proved that the beta decay of Co^{60} behaves like a lefthanded screw or possesses a negative helicity. So

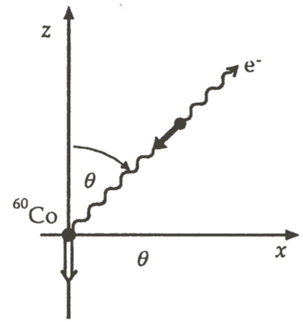
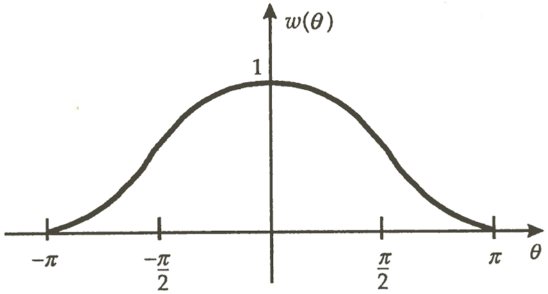


Fig. 1.8. The angular distribution of the electrons in the ^{60}Co decay

(3)

$$\chi_\theta^{(+)} = \begin{pmatrix} \cos\frac{1}{2}\theta \\ \sin\frac{1}{2}\theta \end{pmatrix} \quad , \quad \chi_\theta^{(-)} = \begin{pmatrix} -\sin\frac{1}{2}\theta \\ \cos\frac{1}{2}\theta \end{pmatrix}$$

$$W(\theta) = \left| \langle \chi_{\theta=0}^{(-)} | \chi_\theta^{(-)} \rangle \right|^2 = \cos^2\frac{1}{2}\theta = \frac{1}{2}(1+\cos\theta)$$



(2) Wu, C.S. 1959. Parity Experiments in Beta Decays. Reviews of Modern Physics. 31(3): 783-790.
(3) Greiner W, Müller B. 1996. Gauge Theory of Weak Interactions. Second Edition. Springer.

The Left-Handed Neutrino

Moreover, the asymmetry observed is as large as possible. In the electron angular distribution $I(\theta) = 1 + A\langle J_Z\rangle/J(v/c)\cos\theta$ (where θ is the angle between the nuclear spin and electron momentum direction), the measured asymmetry parameter A is nearly equal to -1. This implies that the parity interference effects

When the experimental value of the asymmetry parameter ($A \cong -1$) in Co^{60} beta decay was made known to Lee and Yang, they immediately realized that here one had to consider an extremely simple and appealing theory of the neutrino.[3] This theory requires that the spin of a neutrino always be either parallel or antiparallel to its momentum and the helicity of an antineutrino be opposite to that of a neutrino. Inci-

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] $0-$, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{\mathbf{p}}_\nu = -1$ (negative helicity).

(3)

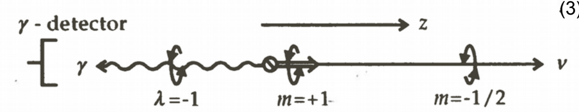


Fig. 1.10. Schematic representation of the experiment of Goldhaber, Grodzins, and Sunyar

V-A Form of the Weak Interaction

$$\hat{P}'_{\pm} = \frac{1}{2}(1 \pm \gamma_5)$$

$$\hat{O}'_i = \hat{P}'_+ \hat{O}_i \hat{P}'_-$$

	$\hat{O}_i$	$\hat{O}'_i$
S	1	0
V	γ^μ	$\gamma^\mu \hat{P}'_- = \frac{1}{2}\gamma^\mu(1-\gamma_5)$
T	$\sigma^{\mu\nu}$	0
A	$\gamma^\mu\gamma_5$	$-\gamma^\mu \hat{P}'_- = -\frac{1}{2}\gamma^\mu(1-\gamma_5)$
P	γ_5	0

(3)

If we neglect the factor 1/2, the only possible coupling is thus

$$\gamma^\mu(1-\gamma_5) = \gamma^\mu - \gamma^\mu\gamma_5 \quad . \tag{1.27}$$

It is obviously of V–A type (pronounced "V minus A"); one thus speaks of V–A coupling.[8]

Quark Mixing

UNITARY SYMMETRY AND LEPTONIC DECAYS

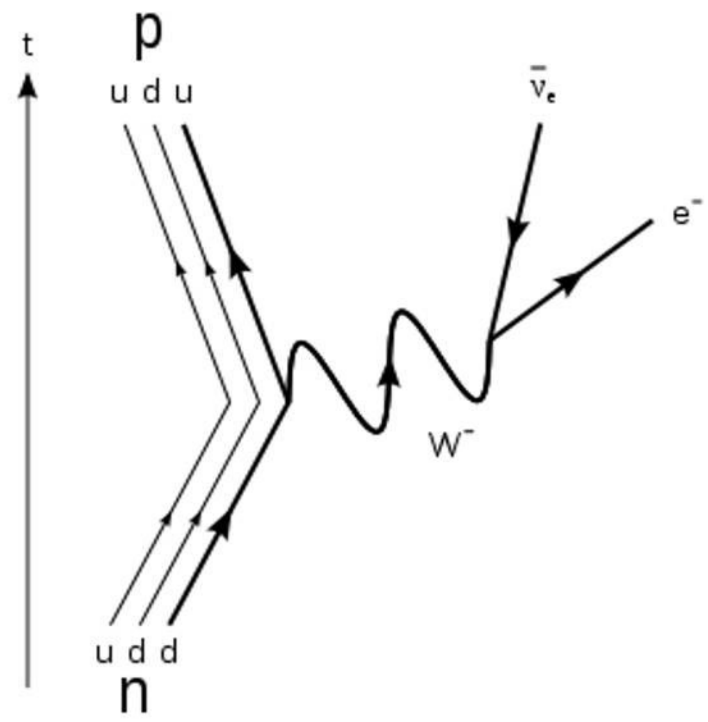
Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

$$J_\mu = \cos\theta(j_\mu^{(0)} + g_\mu^{(0)}) + \sin\theta(j_\mu^{(1)} + g_\mu^{(1)}),$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{sb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

"quark mixing". In the early 1960's, it was observed that, while purely leptonic muon decay proceeds with a strength given by G_F^2, semileptonic neutron or nuclear decays proceed only with $0.95 \times G_F^2$, while strangeness-changing decays of strange particles (like Σ, Λ, Ξ-baryons or K-mesons) proceed with $0.05 \times G_F^2$. Cabibbo then postulated that the down quark state d' that participates in the weak interaction is not the ordinary mass eigenstate d but has a small admixture of strange quark state s, and the strange quark has a small admixture of d, such that $d' = d\cos\theta_C + s\sin\theta_C$, $s' = -d\sin\theta_C + s\cos\theta_C$. The

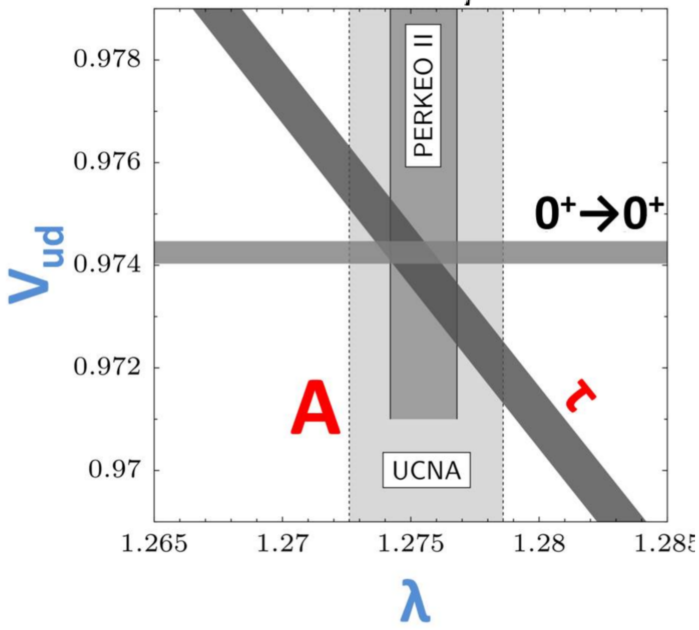
The Weak Interaction



- Down quark changes to Up quark
- Antineutrino and electron produced
- Mediating particles in beta decay include W^+ and W^-

Weak Matrix Element

$$\mathcal{M}_{neutron} = \frac{G_F}{\sqrt{2}} V_{ud} [p(\gamma_\mu (1+\lambda\gamma_5) + \frac{\kappa_p - \kappa_n}{2M} \sigma_{\mu\nu} q^\nu) n] \times [e\gamma_\mu (1-\gamma_5)\nu_e].$$ (4)



$$\lambda = g_A / g_V$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{sb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

(4) Dubbers D, Schmidt M. 2011. The neutron and its role in cosmology and particle physics. arXiv.

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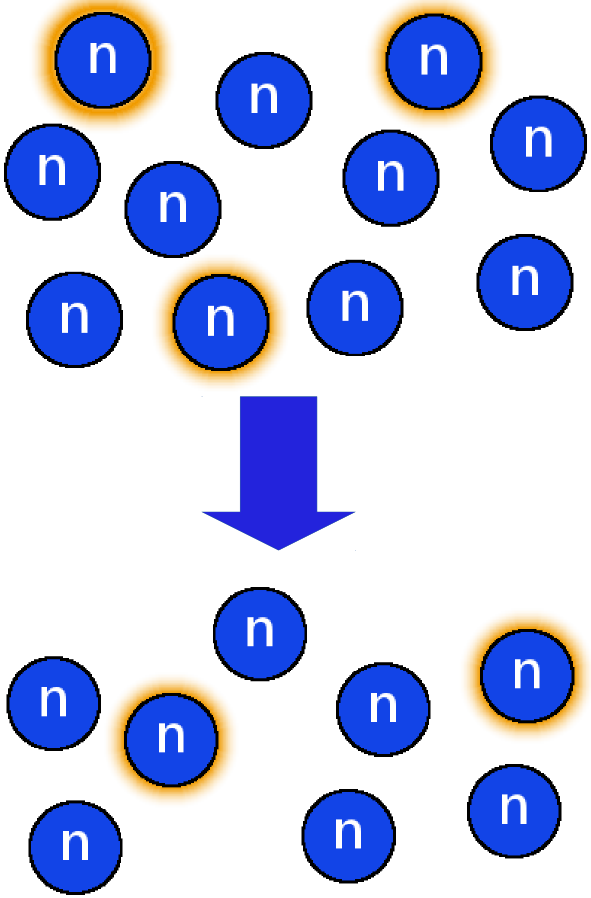
Neutron Lifetime



$$\tau_n^{-1} = \frac{c}{2\pi^3}\frac{(m_e c^2)^5}{(\hbar c)^7} G_F^2 \, |V_{ud}|^2 (1+3\lambda^2) f$$

After corrections for radiative effects and weak magnetism, the lifetime becomes (Marciano and Sirlin, 2006)

$$\tau_n = \frac{(4908.7 \pm 1.9)\ \mathrm{s}}{|V_{ud}|^2 (1+3\lambda^2)},$$

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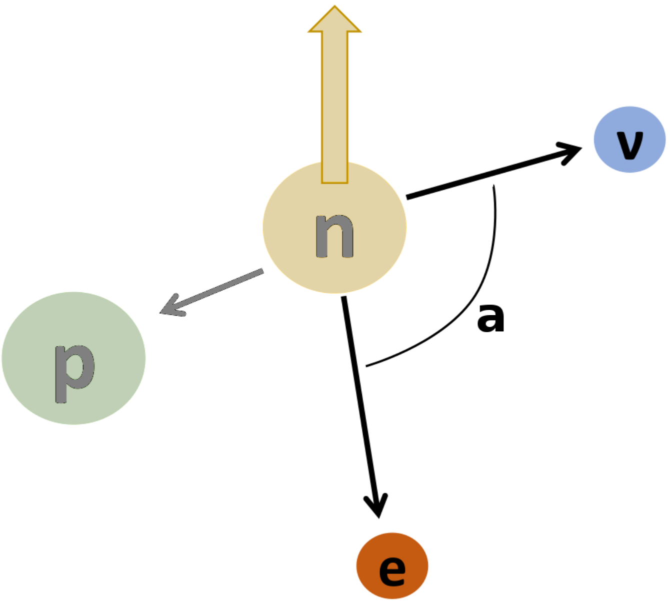
a

electron momentum – neutrino momentum

$$d^2\Gamma \propto \left(1 + a\frac{c\mathbf{p}_e \cdot c\mathbf{p}_\nu}{W_e W_\nu}\right) d\Omega_e = \left(1 + a\frac{v_e}{c}\cos\theta\right) d\Omega_e \qquad a = \frac{1-\lambda^2}{1+3\lambda^2}$$

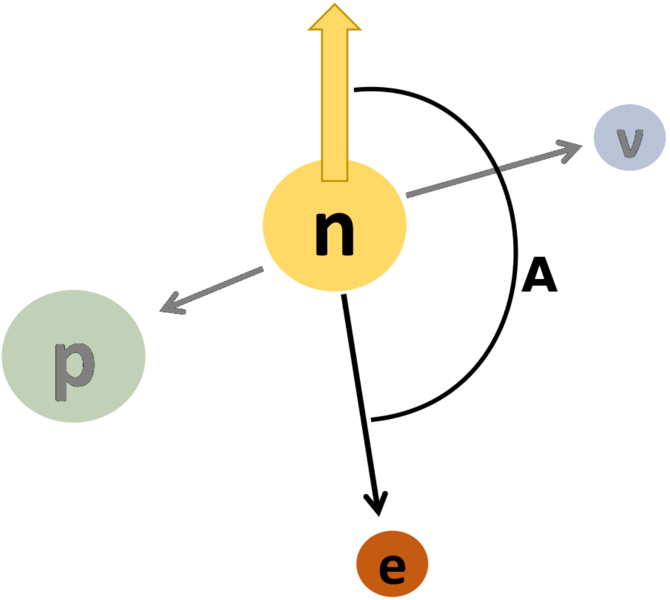


As a measures the deviation of λ^2 from 1, it is highly sensitive to the violation of axial vector current conservation (PCAC), with $\partial_\lambda a / a = -2.8$ at $a \approx -0.10$ (for $\lambda \approx -1.27$, where ∂_λ stands for $\partial / \partial\lambda$).

A

neutron spin – electron momentum

$$d^2\Gamma \propto (1 + A\langle \boldsymbol{\sigma}_n \rangle \cdot \frac{c\mathbf{p}_e}{W_e})\ d\Omega_e = (1 + AP_n \frac{v_e}{c} \cos\theta)\ d\Omega_e$$



$$A = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

$$\partial_\lambda A / A = -3.2 \text{ at } A \approx -0.12$$

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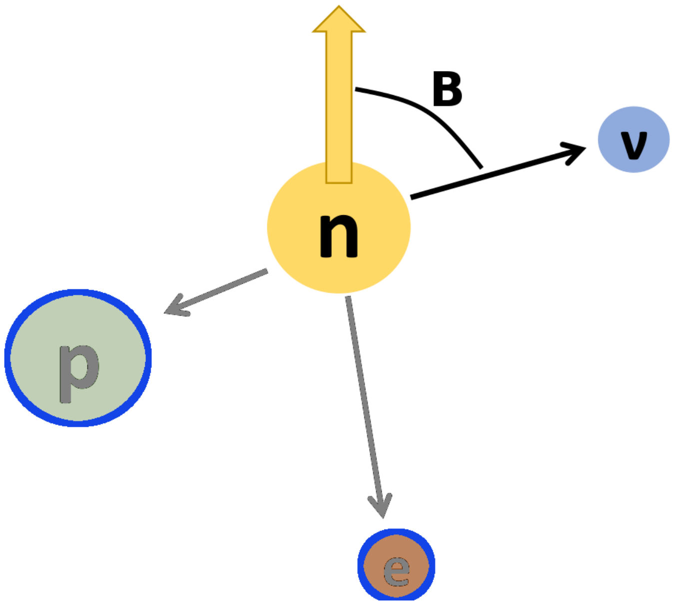
B

neutron spin – neutrino momentum

$$d^2\Gamma \propto \left(1 + B\langle \boldsymbol{\sigma}_n \rangle \cdot \frac{c\mathbf{p}_\nu}{W_\nu}\right) d\Omega_e = (1 + BP_n \cos\theta)\, d\Omega_e$$



$$B = 2\frac{\lambda(\lambda - 1)}{1 + 3\lambda^2}$$

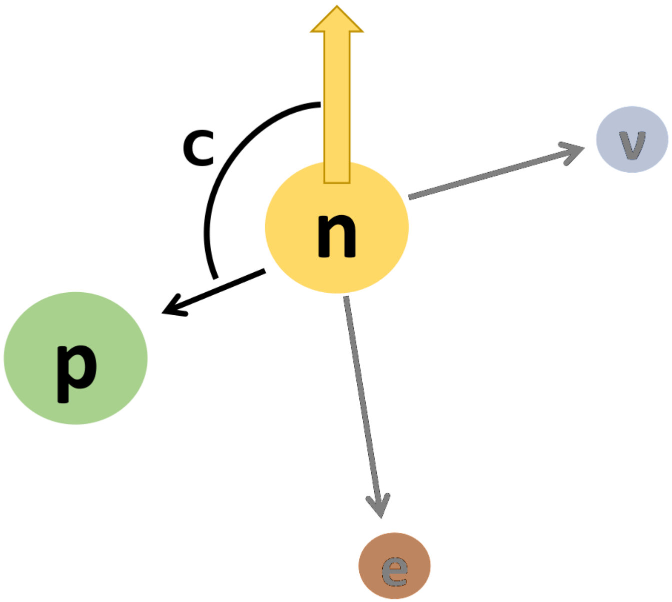
With $\partial_\lambda B / B = 0.077$ at $B \approx 1.0$, the parameter B is about 40 times less sensitive to variations of λ than are the parameters A and a. This makes B valuable for searches of decay amplitudes beyond the SM, as we

C

Los Alamos
NATIONAL LABORATORY
EST. 1943

neutron spin – proton momentum

$$W(\theta) = 1 + 2CP_n \cos\theta$$



$$C = x_C \frac{4\lambda}{1+3\lambda^2} = -x_C(A+B)$$

$$\partial_\lambda C / C = 0.52 \text{ at } C \approx 0.24$$

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Electron Spin Correlations

- G: electron spin – electron momentum
  - In SM, = -1
- H: electron spin – neutrino momentum
- N: electron spin – neutron spin

$$H = -\frac{m_e}{W_e} a \text{, and } N = -\frac{m_e}{W_e} A$$

$$\omega(\boldsymbol{\sigma} | E_e, \Omega_e, \Omega_\nu) dE_e d\Omega_e d\Omega_\nu$$
$$= \frac{1}{(2\pi)^5} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu$$
$$\times \tfrac{1}{2}\xi \left\{ 1 + a\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b\frac{m}{E_e} + \boldsymbol{\sigma} \cdot \left[G\frac{\mathbf{p}_e}{E_e} + H\frac{\mathbf{p}_\nu}{E_\nu} \right.\right.$$
$$\left.\left. + K\frac{\mathbf{p}_e}{E_e + m}\left(\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu}\right) + L\frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right] \right\}. \quad (3)$$

$$\omega(\langle \mathbf{J} \rangle, \boldsymbol{\sigma} | E_e, \Omega_e) dE_e d\Omega_e$$
$$= \frac{1}{(2\pi)^4} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e$$
$$\times \xi \left\{ 1 + b\frac{m}{E_e} + \left(A\frac{\langle \mathbf{J} \rangle}{J} + G\boldsymbol{\sigma} \right) \cdot \frac{\mathbf{p}_e}{E_e} + \boldsymbol{\sigma} \cdot \left[N\frac{\langle \mathbf{J} \rangle}{J} \right.\right.$$
$$\left.\left. + Q\frac{\mathbf{p}_e}{E_e + m}\left(\frac{\langle \mathbf{J} \rangle}{J} \cdot \frac{\mathbf{p}_e}{E_e}\right) + R\frac{\langle \mathbf{J} \rangle}{J} \times \frac{\mathbf{p}_e}{E_e} \right] \right\}. \quad (6)$$

Threefold Correlations

$$D = \boldsymbol{\sigma}_n \cdot (\mathbf{p}_e \times \mathbf{p}_\nu) \qquad L = \boldsymbol{\sigma}_e \cdot (\mathbf{p}_e \times \mathbf{p}_\nu)$$

$$R = \boldsymbol{\sigma}_e \cdot (\boldsymbol{\sigma}_n \times \mathbf{p}_e) \qquad V = \boldsymbol{\sigma}_n \cdot (\boldsymbol{\sigma}_e \times \mathbf{p}_\nu)$$

All triple products are T-violating

L and R potential BSM searches

D immeasurably small, V proportional to D

Fourfold/Fivefold Correlations

$$K = (\boldsymbol{\sigma}_n \cdot \mathbf{p}_e)(\mathbf{p}_e \cdot \mathbf{p}_\nu) \qquad Q = (\boldsymbol{\sigma}_e \cdot \mathbf{p}_e)(\boldsymbol{\sigma}_n \cdot \mathbf{p}_\nu)$$

$$S = (\boldsymbol{\sigma}_e \cdot \boldsymbol{\sigma}_n)(\mathbf{p}_e \cdot \mathbf{p}_\nu) \qquad T = (\boldsymbol{\sigma}_e \cdot \mathbf{p}_e)(\boldsymbol{\sigma}_n \cdot \mathbf{p}_\nu)$$

$$U = (\boldsymbol{\sigma}_e \cdot \mathbf{p}_\nu)(\boldsymbol{\sigma}_n \cdot \mathbf{p}_e)$$

However, in the SM,

$$K = -A \qquad Q = -A$$

$$S = 0 \qquad T = -B$$

$$U \approx 0$$

BSM Searches: b and b_ν

- Fierz term shifts the neutron beta spectrum

$$P_b = P_{\mathrm{SM}}\left(\frac{1+b\frac{m_e}{E_e}}{1+b\left\langle\frac{m_e}{E_e}\right\rangle}\right)$$

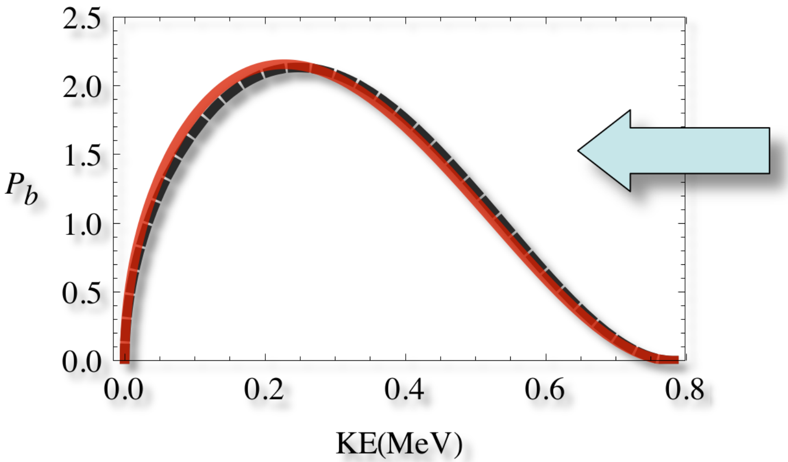

Image by Kevin Hickerson. 2009. UCN Workshop. Santa Fe, NM.

$$\tilde{Y}(E_e) = \frac{\bar{Y}(E_e)}{1+\bar{b}m_e/E_e},$$

where $Y \in \{A, B, a, \ldots\}$

Jackson, Treiman, and Wyld

Los Alamos NATIONAL LABORATORY EST.1943

II. RECOIL EXPERIMENTS WITH ORIENTED NUCLEI

$$\omega(\langle J\rangle|E_e,\Omega_e,\Omega_\nu)dE_e d\Omega_e d\Omega_\nu$$
$$=\frac{1}{(2\pi)^5}p_eE_e(E^0-E_e)^2dE_ed\Omega_ed\Omega_\nu\xi\bigg\{1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+b\frac{m}{E_e}$$
$$+c\left[\frac{1}{3}\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}-\frac{(\mathbf{p}_e\cdot\mathbf{j})(\mathbf{p}_\nu\cdot\mathbf{j})}{E_eE_\nu}\right]\left[\frac{J(J+1)-3\langle(\mathbf{J}\cdot\mathbf{j})^2\rangle}{J(2J-1)}\right]$$
$$+\frac{\langle\mathbf{J}\rangle}{J}\cdot\left[A\frac{\mathbf{p}_e}{E_e}+B\frac{\mathbf{p}_\nu}{E_\nu}+D\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]\bigg\}. \quad (2)$$

III. ELECTRON POLARIZATION IN RECOIL EXPERIMENT

$$\omega(\boldsymbol{\sigma}|E_e,\Omega_e,\Omega_\nu)dE_ed\Omega_ed\Omega_\nu$$
$$=\frac{1}{(2\pi)^5}p_eE_e(E^0-E_e)^2dE_ed\Omega_ed\Omega_\nu$$
$$\times\tfrac{1}{2}\xi\bigg\{1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+b\frac{m}{E_e}+\boldsymbol{\sigma}\cdot\left[G\frac{\mathbf{p}_e}{E_e}+H\frac{\mathbf{p}_\nu}{E_\nu}\right.$$
$$\left.+K\frac{\mathbf{p}_e}{E_e+m}\left(\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}\right)+L\frac{\mathbf{p}_e\times\mathbf{p}_\nu}{E_eE_\nu}\right]\bigg\}. \quad (3)$$

IV. ELECTRON POLARIZATION IN DECAY OF ORIENTED NUCLEI

$$\omega(\langle\mathbf{J}\rangle,\boldsymbol{\sigma}|E_e,\Omega_e)dE_ed\Omega_e$$
$$=\frac{1}{(2\pi)^4}p_eE_e(E^0-E_e)^2dE_ed\Omega_e$$
$$\times\xi\bigg\{1+b\frac{m}{E_e}+\left(A\frac{\langle\mathbf{J}\rangle}{J}+G\boldsymbol{\sigma}\right)\cdot\frac{\mathbf{p}_e}{E_e}+\boldsymbol{\sigma}\cdot\left[N\frac{\langle\mathbf{J}\rangle}{J}\right.$$
$$\left.+Q\frac{\mathbf{p}_e}{E_e+m}\left(\frac{\langle\mathbf{J}\rangle}{J}\cdot\frac{\mathbf{p}_e}{E_e}\right)+R\frac{\langle\mathbf{J}\rangle}{J}\times\frac{\mathbf{p}_e}{E_e}\right]\bigg\}. \quad (6)$$

BSM Searches: b and b_ν

PHYSICAL REVIEW D **85,** 054512 (2012)

Probing novel scalar and tensor interactions from (ultra)cold neutrons to the LHC

Tanmoy Bhattacharya,[1] Vincenzo Cirigliano,[1] Saul D. Cohen,[2,5] Alberto Filipuzzi,[3] Martín González-Alonso,[4] Michael L. Graesser,[1] Rajan Gupta,[1] and Huey-Wen Lin[5]

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(Received 18 November 2011; published 30 March 2012)

ϵ_S – effective scalar coupling

ϵ_T – effective tensor coupling

ϵ_P – effective pseudoscalar coupling

ϵ_L, ϵ_R – additional left and right handed coupling constants

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BSM Searches: b and b_ν

$$D(E_e, \mathbf{p}_e, \mathbf{p}_\nu, \boldsymbol{\sigma}_n) = 1 + c_0 + c_1 \frac{E_e}{M_N} + \frac{m_e}{E_e}\bar{b} + \bar{a}(E_e)\frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + \bar{A}(E_e)\frac{\boldsymbol{\sigma}_n \cdot \mathbf{p}_e}{E_e} + \bar{B}(E_e)\frac{\boldsymbol{\sigma}_n \cdot \mathbf{p}_\nu}{E_\nu} + \ldots$$

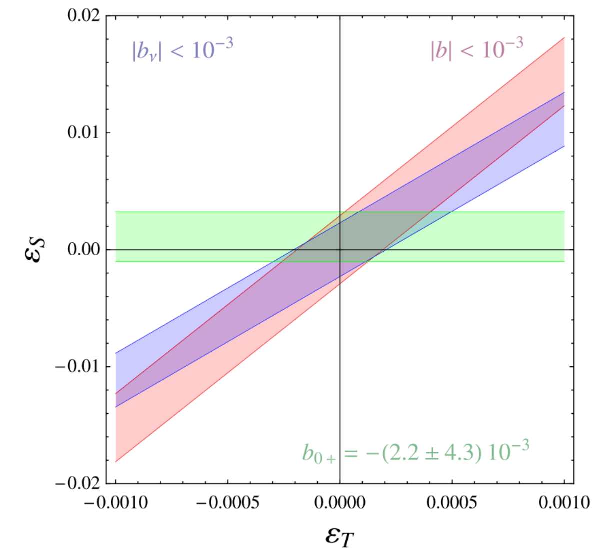
$$\bar{b} = b^{\mathrm{SM}} + b^{\mathrm{BSM}} \qquad \bar{B}(E_e) = B_{\mathrm{LO}}(\tilde{\lambda}) + \ldots + \frac{m_e}{E_e}(b_\nu^{\mathrm{SM}} + b_\nu^{\mathrm{BSM}})$$

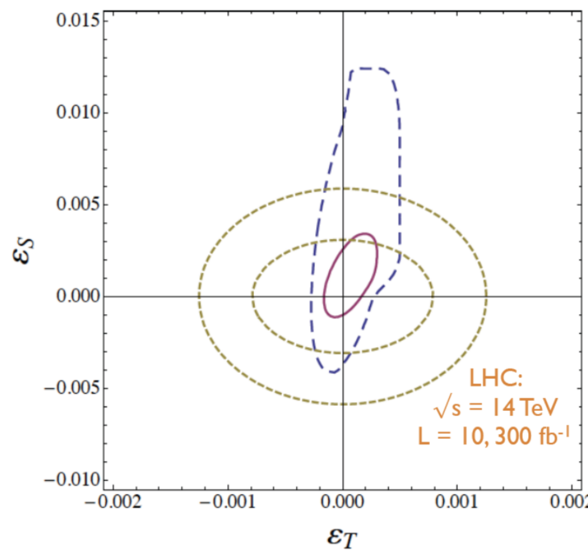
BSM Searches: b and b_ν

$$b^{\rm SM} = -\frac{m_e}{M_N}\frac{1+2\mu_V\lambda+\lambda^2}{1+3\lambda^2}$$

$$b_\nu^{\rm SM} = -\frac{m_e}{M_N}\frac{(1+\lambda)(\mu_V+\lambda)}{1+3\lambda^2}$$

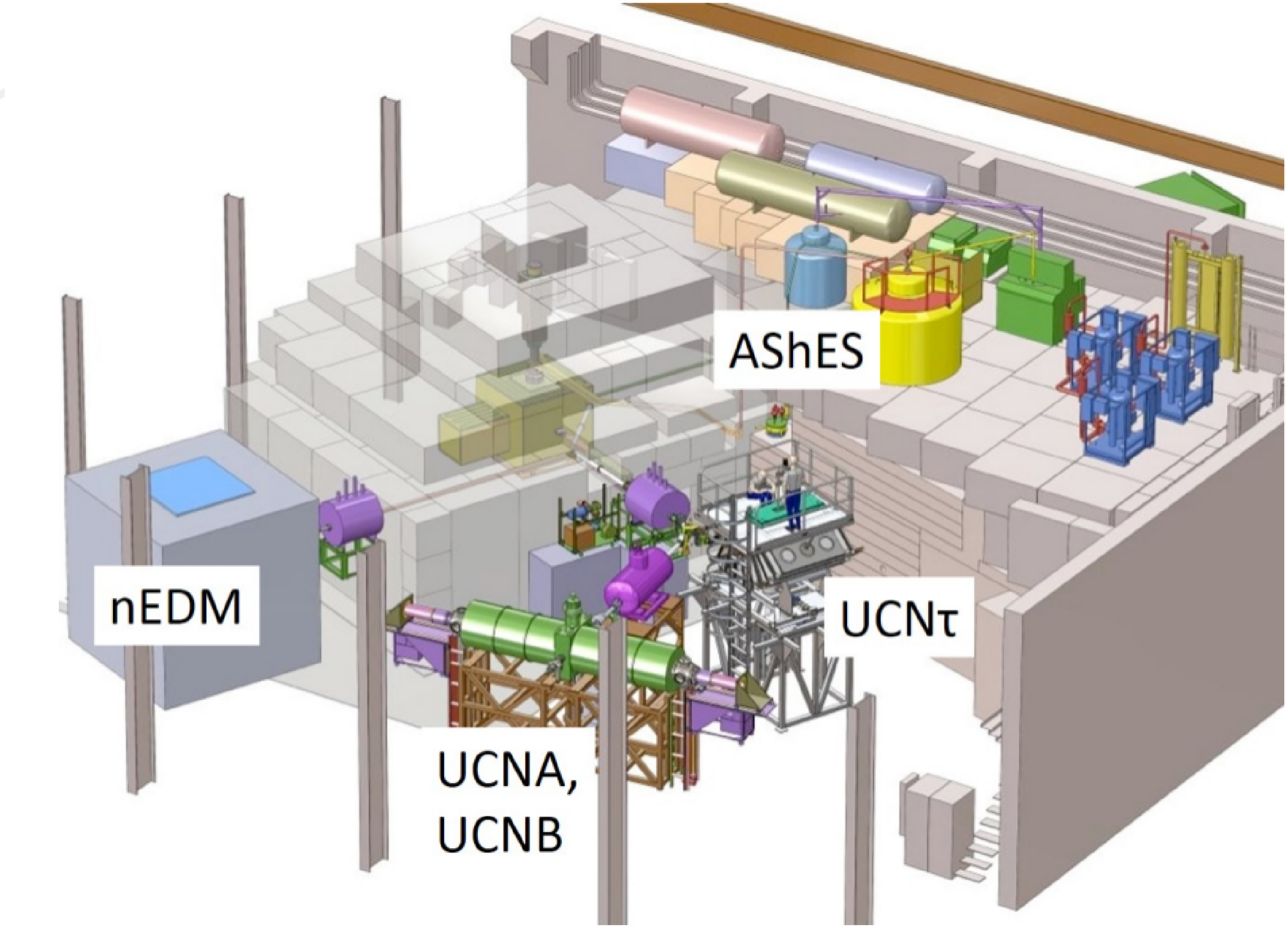
$$\begin{aligned} b^{\rm BSM} &= \frac{2}{1+3\lambda^2}[g_S\epsilon_S - 12\lambda g_T\epsilon_T] \\ &\approx 0.34 g_S\epsilon_S - 5.22 g_T\epsilon_T, \\ b_\nu^{\rm BSM} &= \frac{2}{1+3\lambda^2}[g_S\epsilon_S\lambda - 4g_T\epsilon_T(1+2\lambda)] \\ &\approx 0.44 g_S\epsilon_S - 4.85 g_T\epsilon_T. \end{aligned}$$



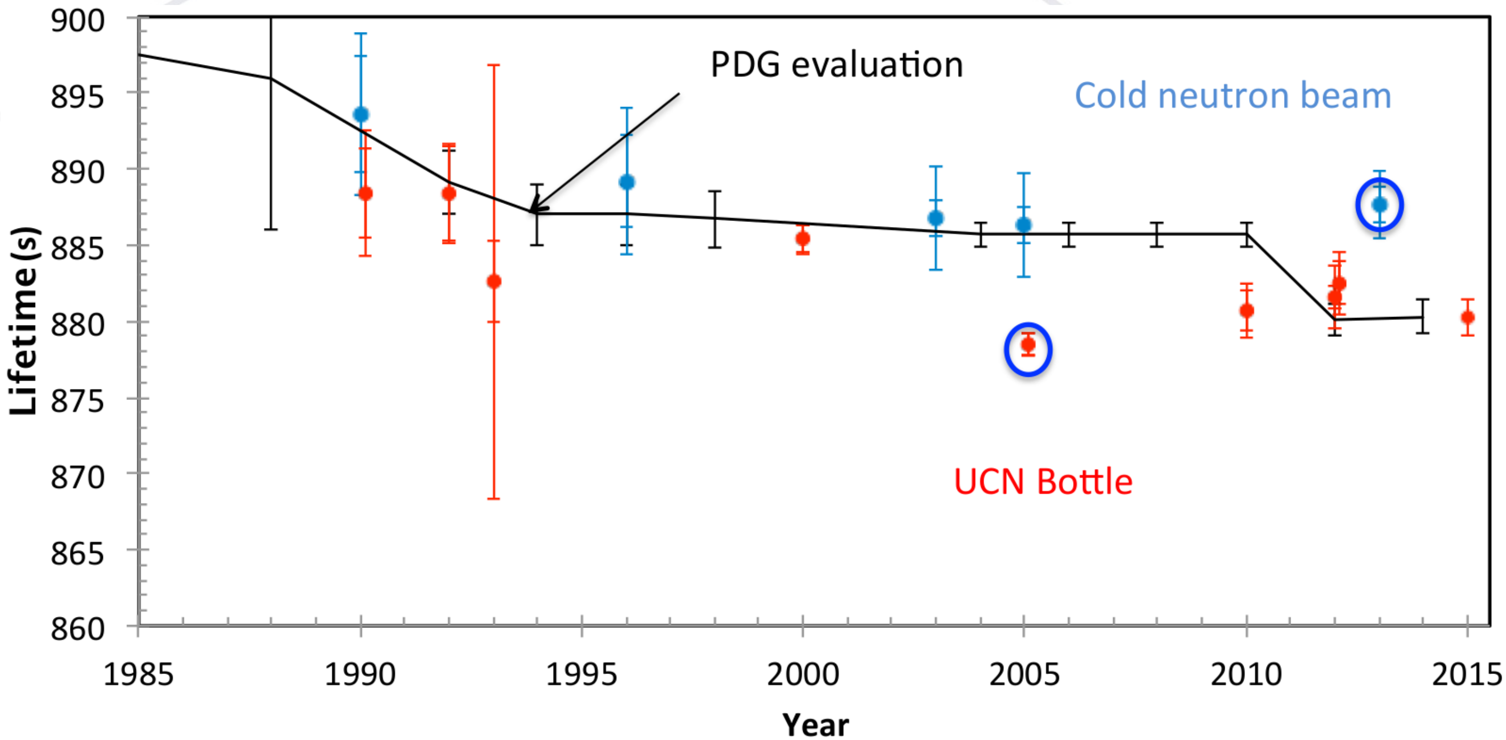


(5) Aprahamian A. et al. White Paper on Fundamental Symmetries. 2015.

UCN at LANSCE



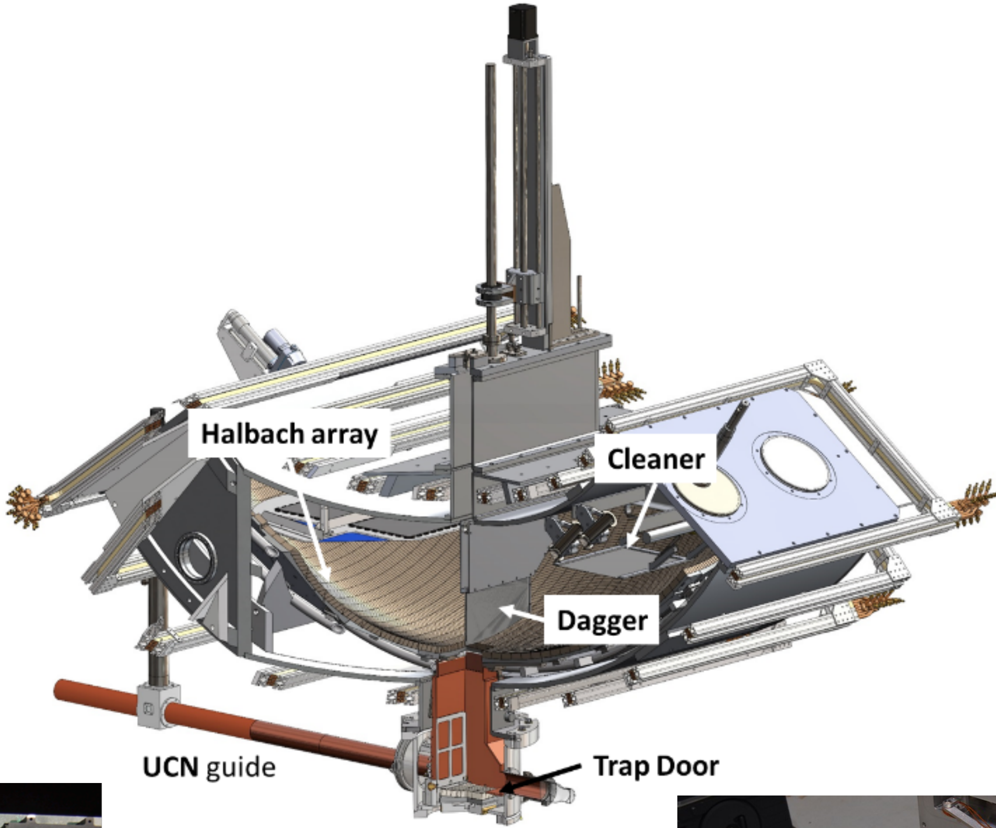
History of τ

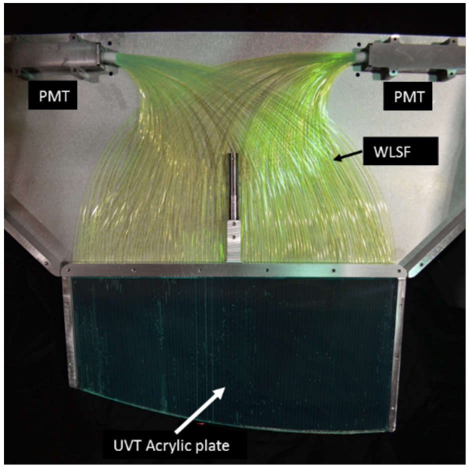


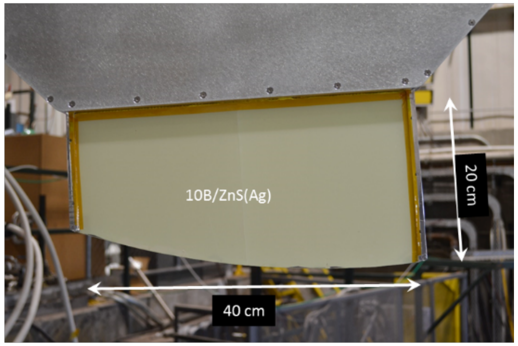
Most precise Beam: $\tau_n = 887.1 \pm 2.2$ s

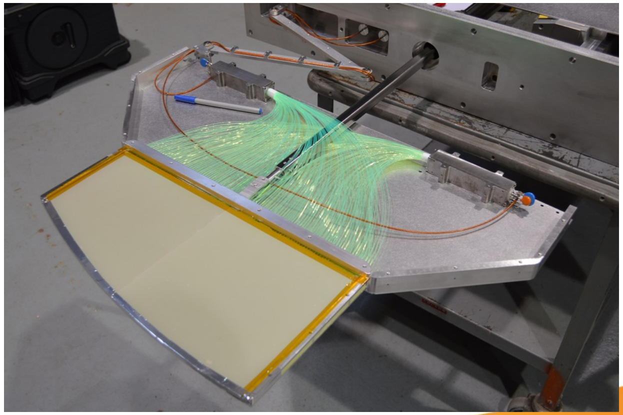
Most precise Bottle: $\tau_n = 878.5 \pm 0.8$ s

UCNτ









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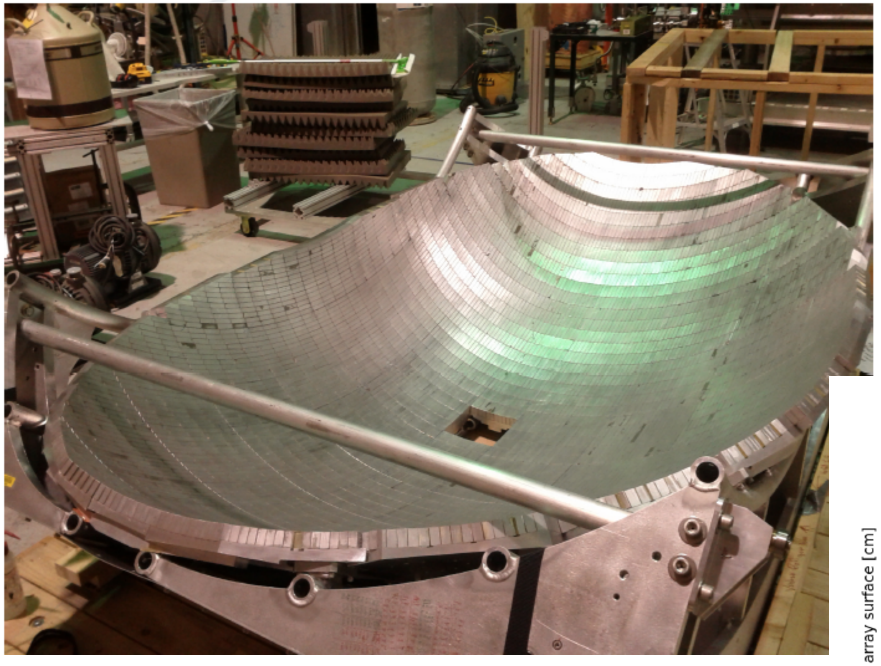
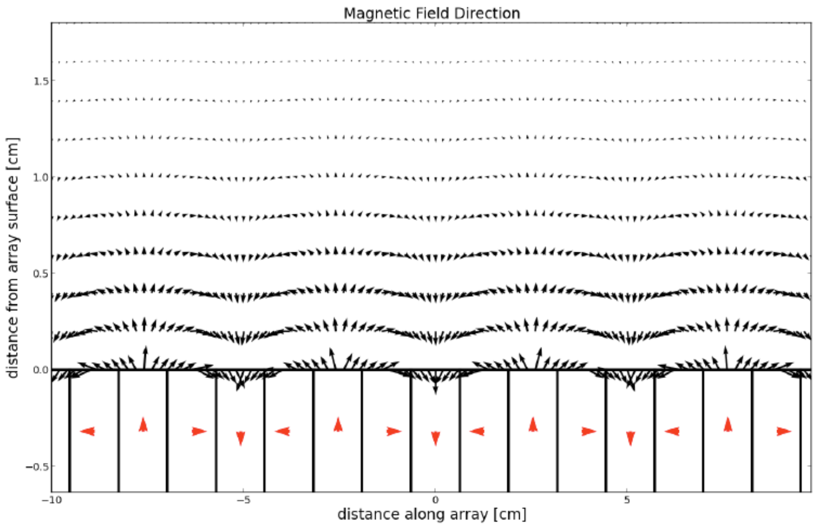
UCN τ




Magnetic Field Direction
distance from array surface [cm]
distance along array [cm]
1.5
1.0
0.5
0.0
−0.5
−10
−5
0
5

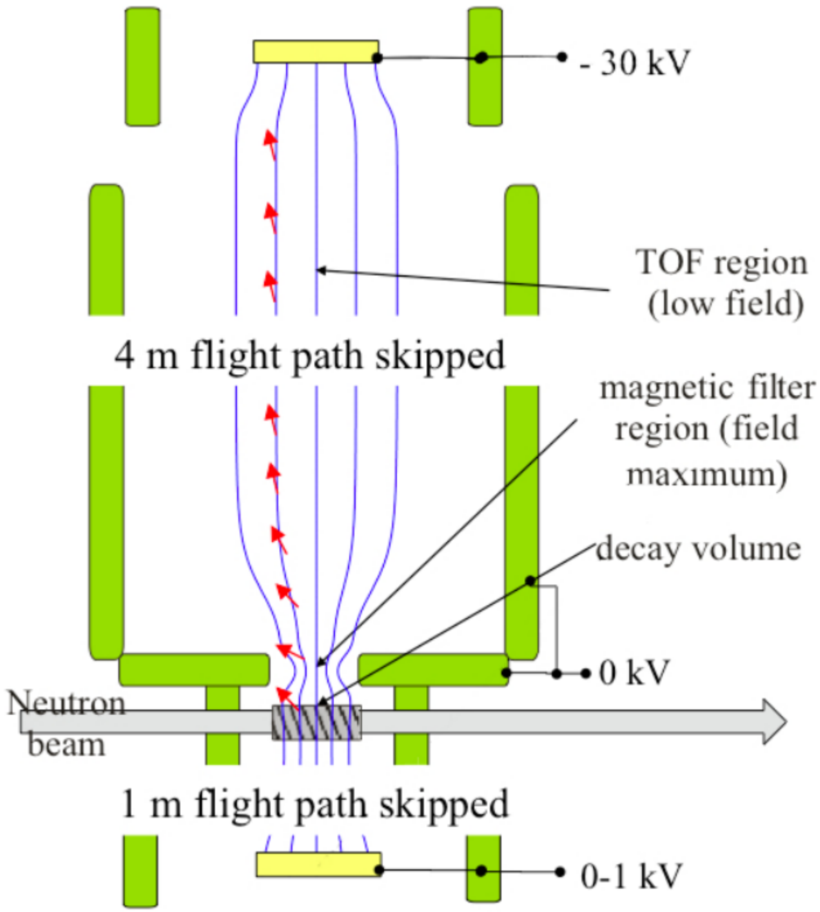
UCN τ

- Goal of 1 second precision after new source commissioning
- Primary efforts towards removing residual gas and resolving UCN spectral variation

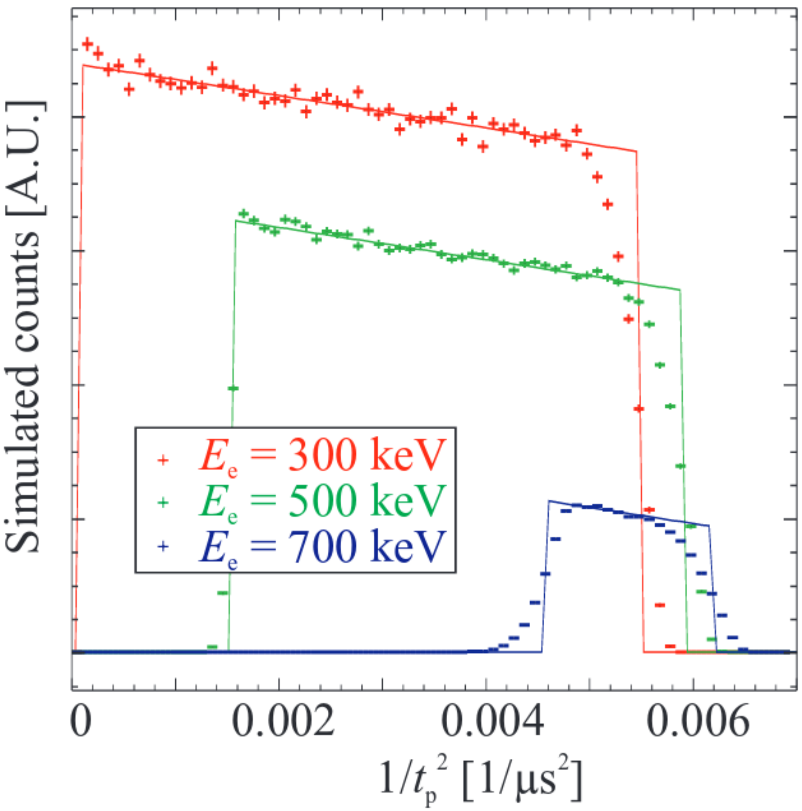
Gas	Maximum Pressure (torr)
H_2	2.6E-07
D_2	1.5E-06
Ne	2.0E-05
Ar	1.8E-05
Xe	6.5E-07
CF_4	1.6E-06
C_4H_{10}	7.1E-08
Air	1.5e-06
^{3}He	3.0E-09

$$\left.\frac{\Delta\tau_n}{\tau_n}\right|_{\tau_{loss}} = \left(\frac{\tau_n}{\tau_{loss}}\right) \times \left(\frac{\Delta\tau_{loss}}{\tau_{loss}}\right) \qquad \left.\frac{\Delta\tau_n}{\tau_n}\right|_{(\tau_{loss})} \leq 10^{-4}$$

Nab



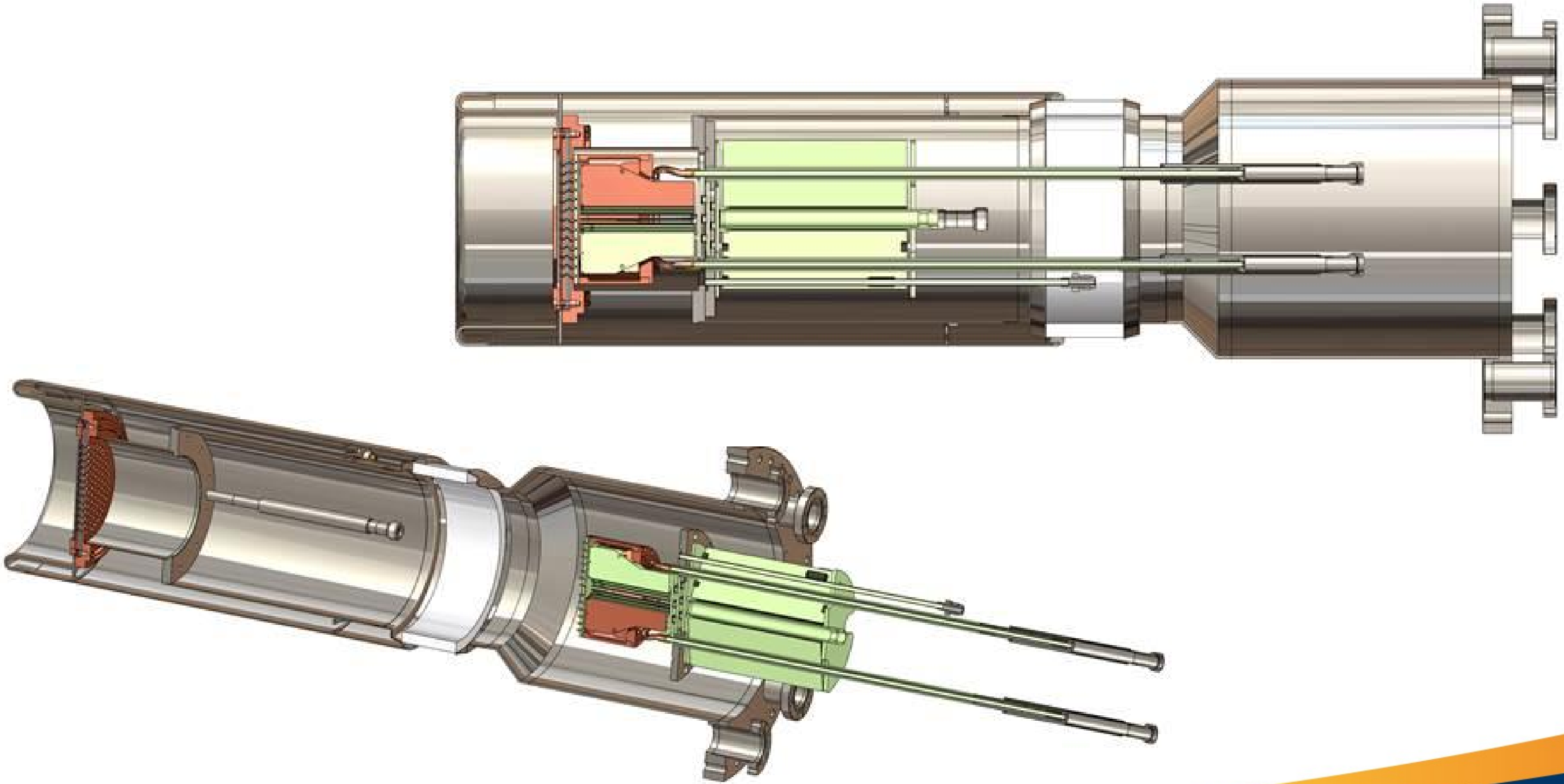
- 30 kV
TOF region
(low field)
4 m flight path skipped
magnetic filter
region (field
maximum)
decay volume
0 kV
Neutron
beam
1 m flight path skipped
0-1 kV



Simulated counts [A.U.]
E_e = 300 keV
E_e = 500 keV
E_e = 700 keV
0
0.002
0.004
0.006
$1/t_p^2$ [1/μs²]

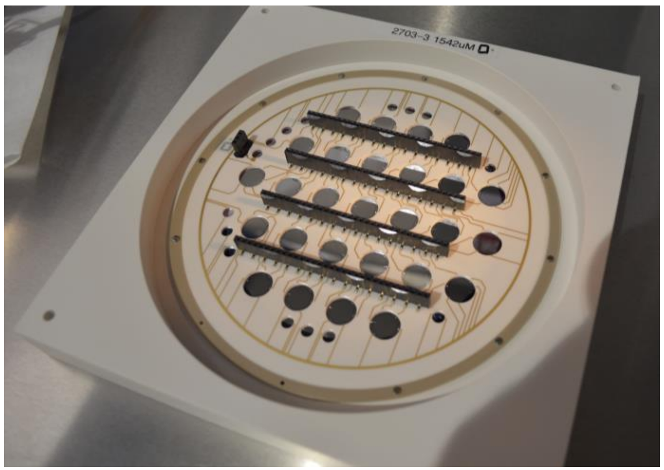
Nab

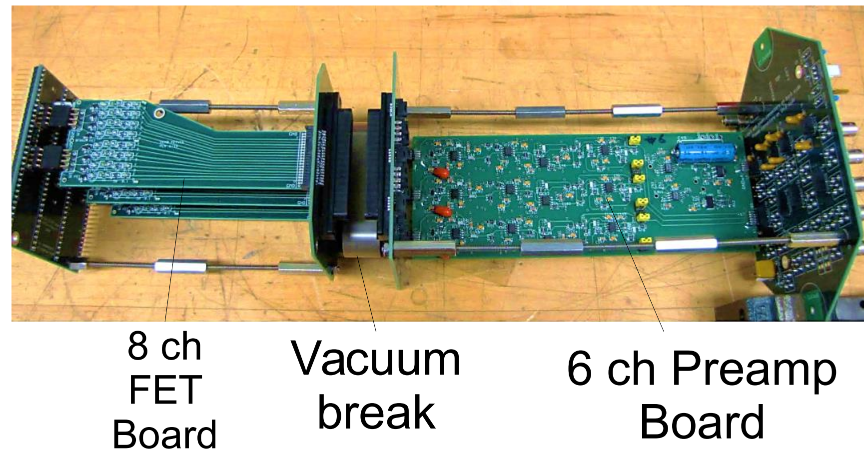
Contributions from the Neutron Team

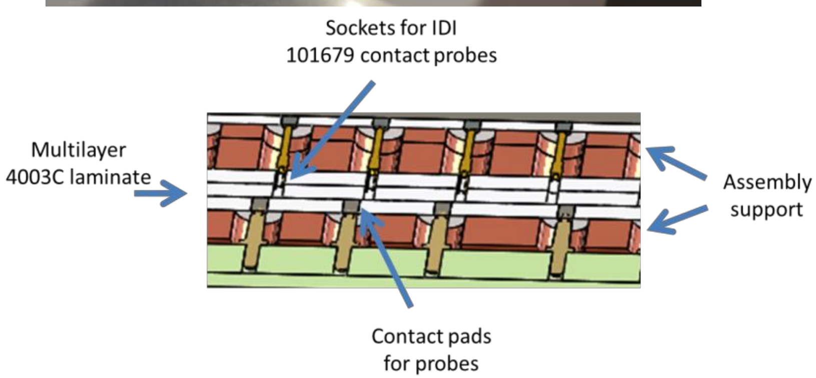


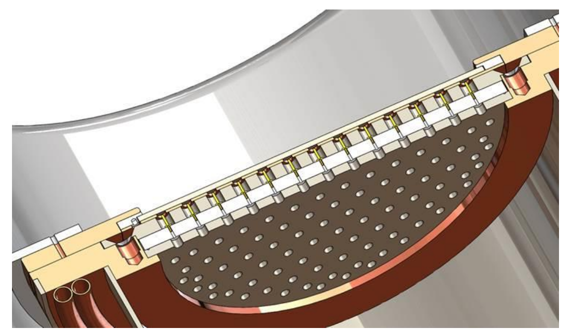
Nab

Contributions from the Neutron Team









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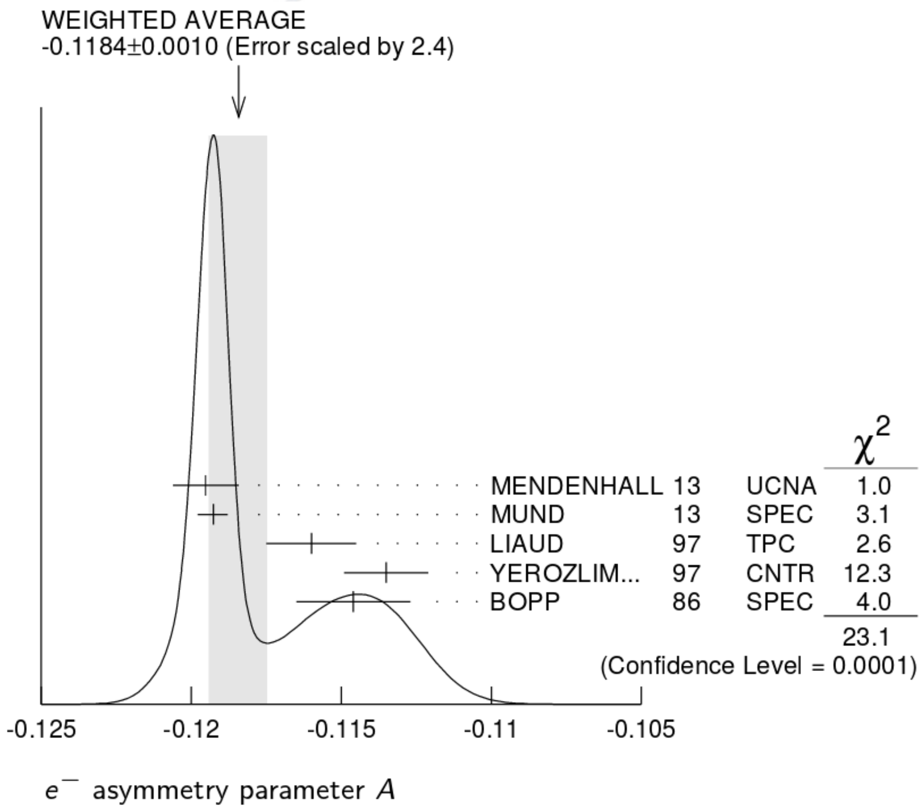
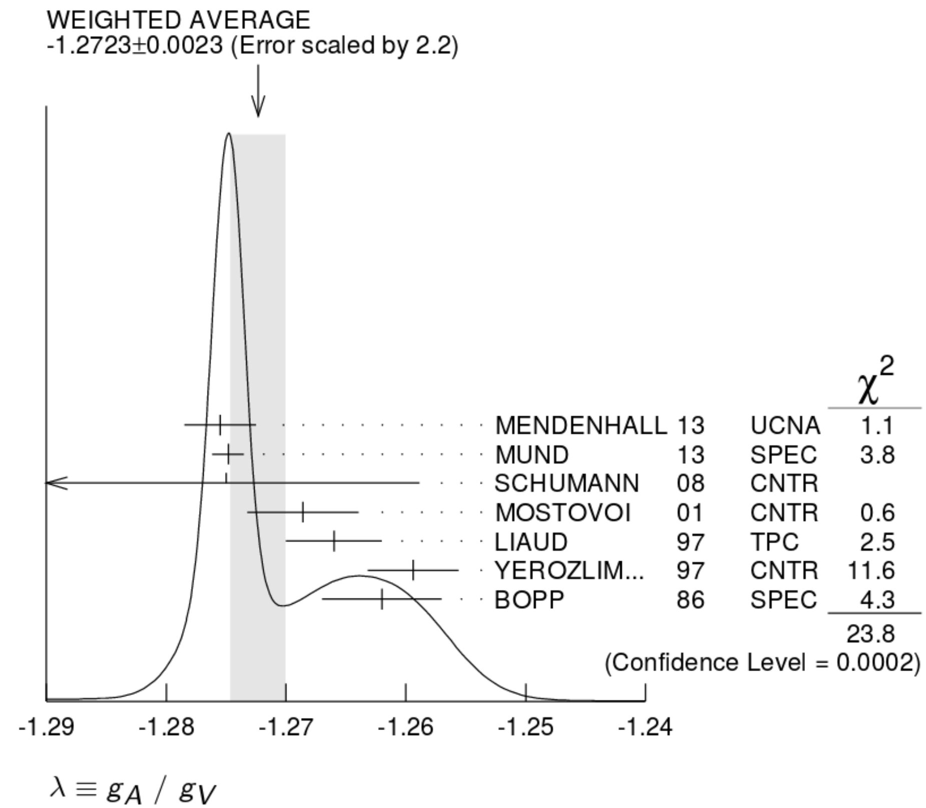
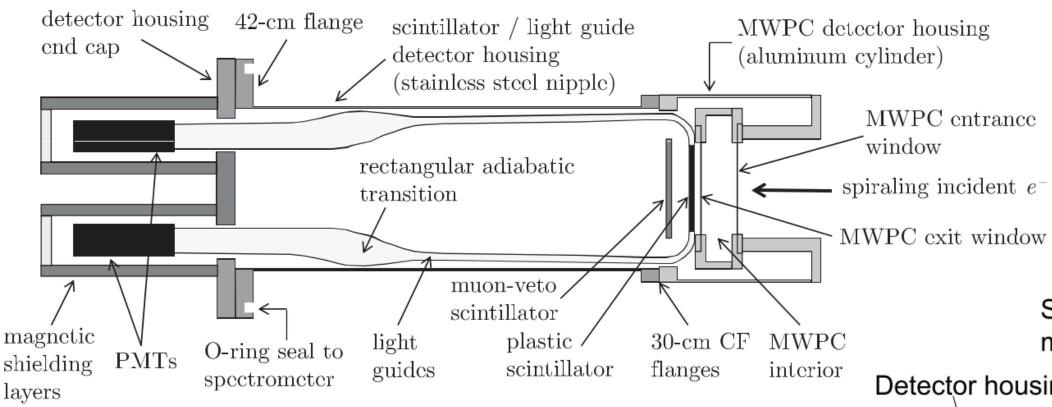
UCNA



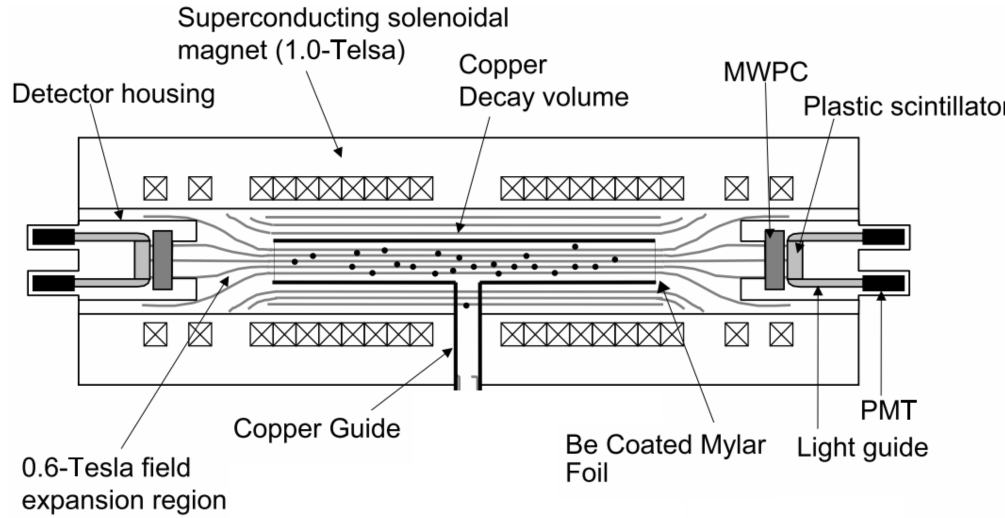


From PDG 2016

UCNA



detector housing end cap
42-cm flange
scintillator / light guide detector housing (stainless steel nipple)
MWPC detector housing (aluminum cylinder)
MWPC entrance window
spiraling incident e^-
MWPC exit window
rectangular adiabatic transition
muon-veto scintillator
magnetic shielding layers
PMTs
O-ring seal to spectrometer
light guides
plastic scintillator
30-cm CF flanges
MWPC interior



Superconducting solenoidal magnet (1.0-Telsa)
Copper Decay volume
MWPC
Plastic scintillator
Detector housing
Copper Guide
0.6-Tesla field expansion region
Be Coated Mylar Foil
PMT
Light guide

UCNA

	2010		2011-2012		2012-2013	
	Correction (%)	Uncertainty (%)	Correction (%)	Uncertainty (%)	Correction (%)	Uncertainty (%)
Polarization	+0.67	±0.56	-	±0.2?	-	±0.2?
$\Delta_{\text{Experimental}}$	+0.13*	±0.45*	+0.5	±0.13	-0.48	±0.12
Energy Recon.		±0.31		±0.32		±0.32
Δ_{Theory}	-1.81	±0.06	-1.81	±0.06	-1.81	±0.06
Δ_{Rest}	+0.19	±0.22		±0.22		±0.22
Statistics		±0.46		±0.45		±0.49
TOTAL	**-0.83**	**±0.94**	**-**	**±0.64**	**-**	**±0.67**
			Combined Uncert.		**±0.57 %**	

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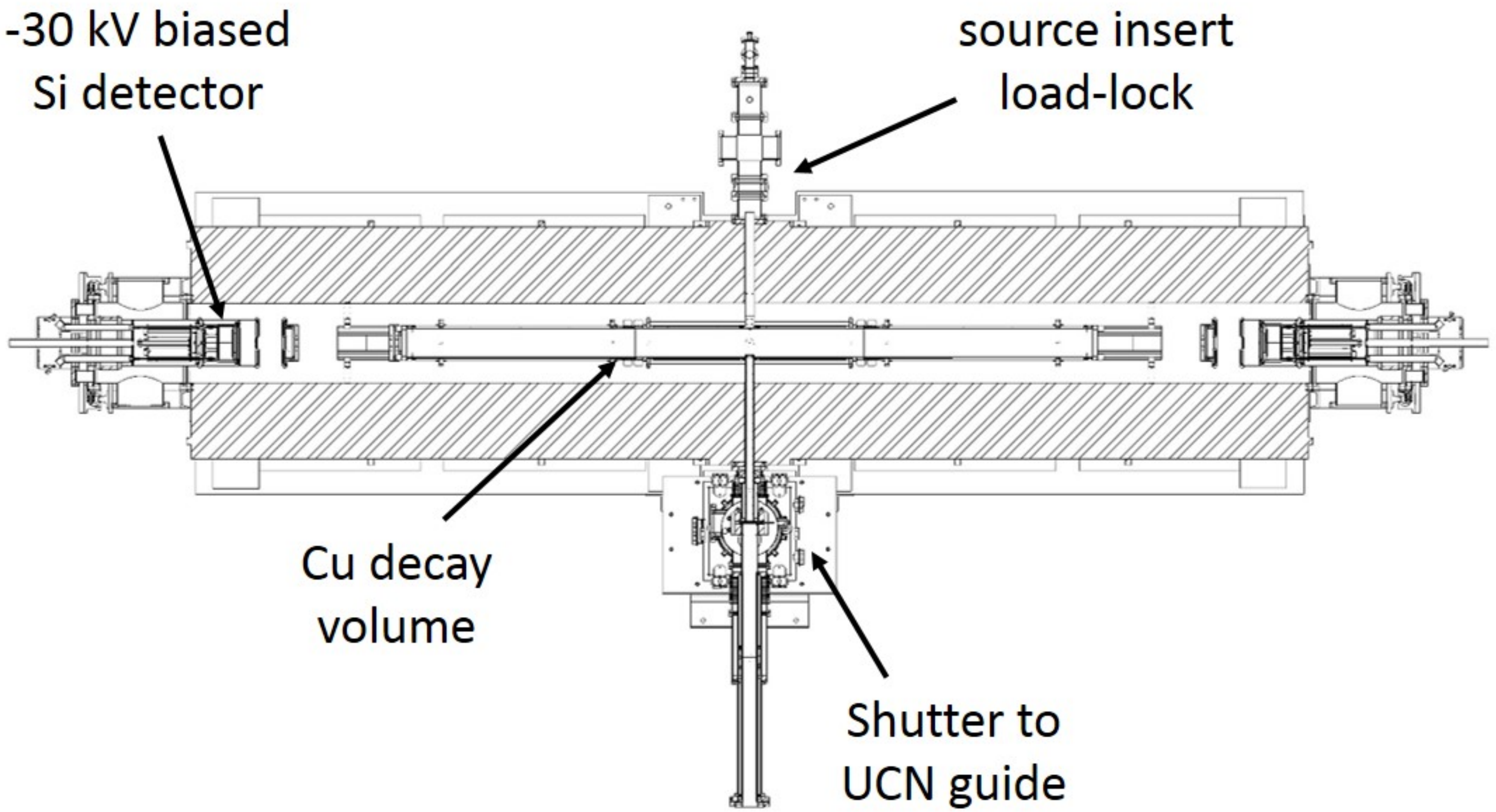
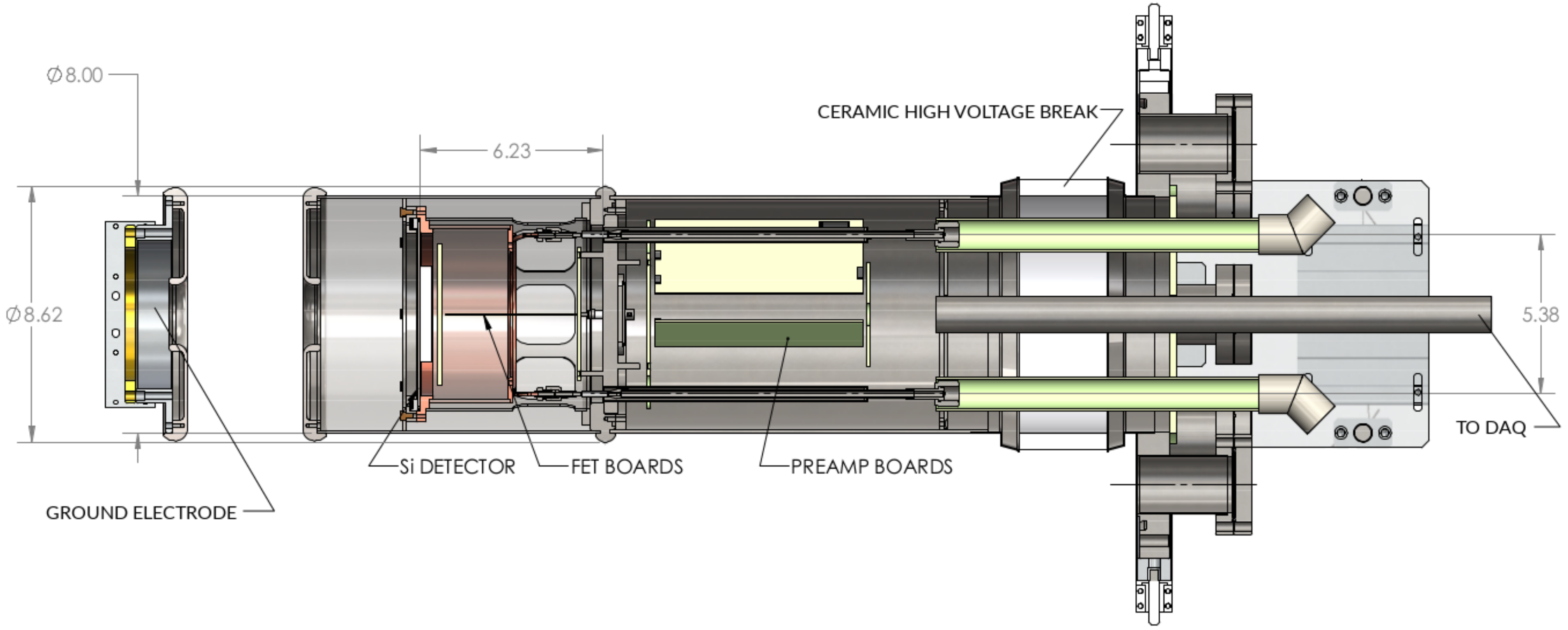
UCNB



-30 kV biased
Si detector
source insert
load-lock
Cu decay
volume
Shutter to
UCN guide

UCNB



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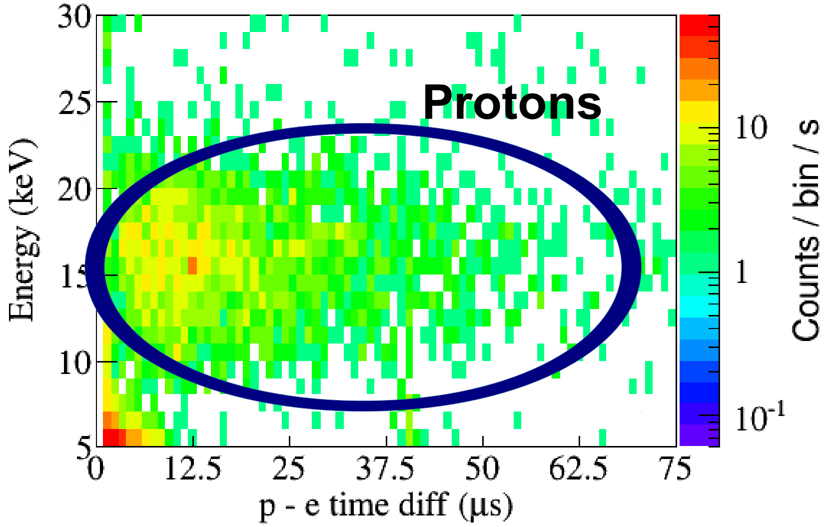
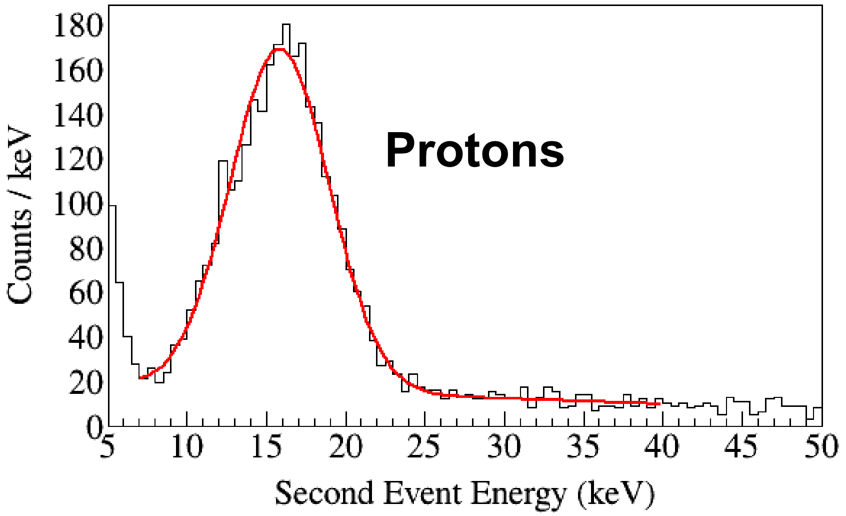
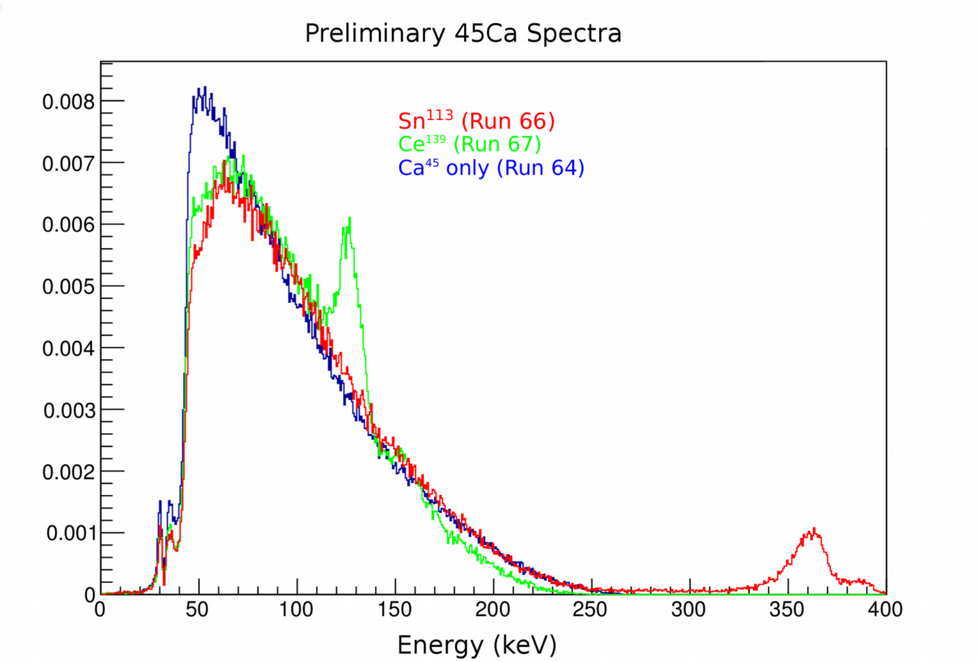
UCNB





- Lack of windows reduces rate
- Only 1 side at HV to date

UCNB\b



Resolution permits measurements of beta decay spectra to measure b in nuclei

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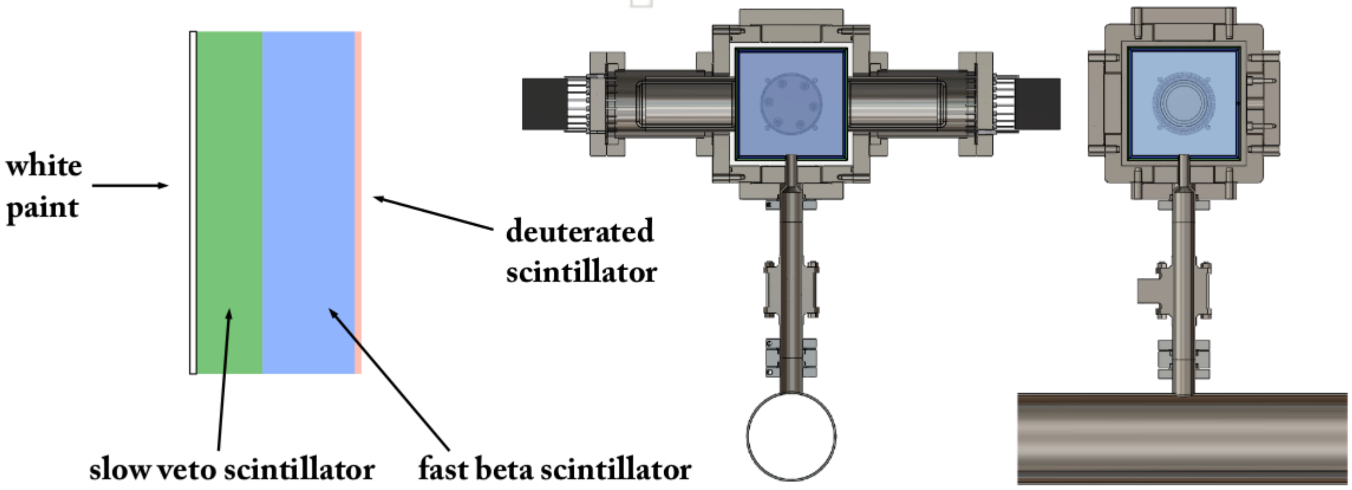
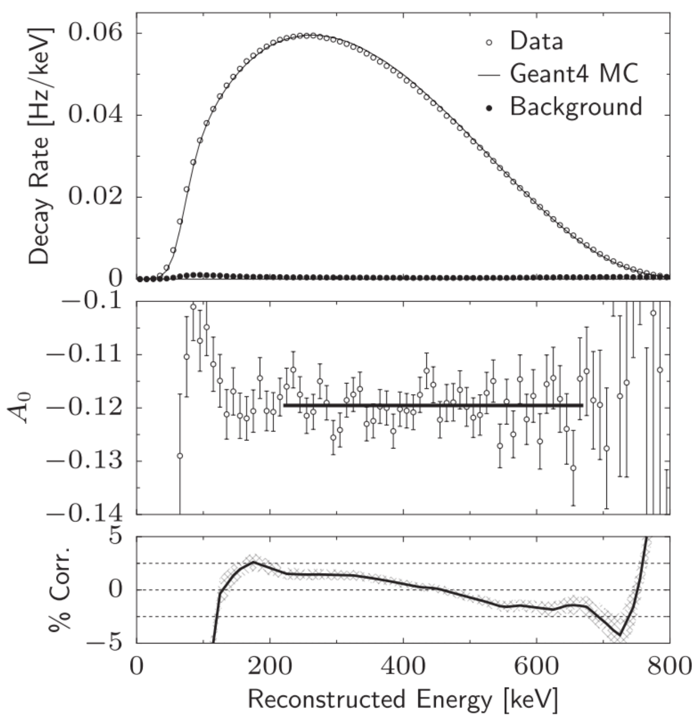
UCNb



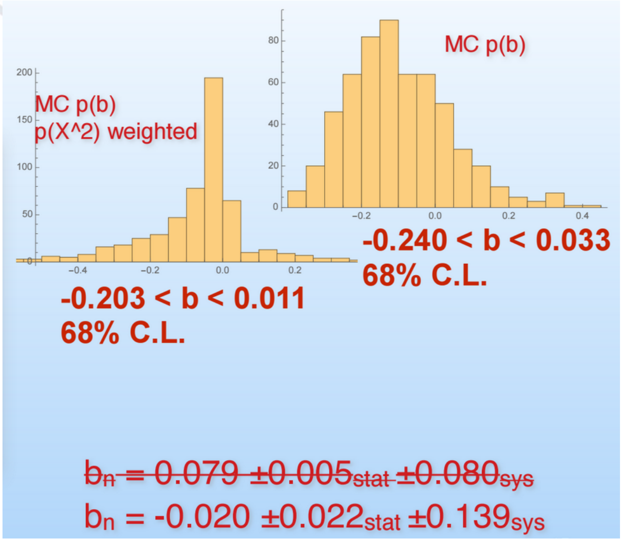
Difficulties from unexpected background and equipment failure

Efforts to measure b



UCNAb

Kevin Hickerson (Caltech) working on extracting b from UCNA



Nab efforts

lower E_e cutoff:	none	100 keV	200 keV	300 keV
σ_b	$7.5/\sqrt{N}$	$10.1/\sqrt{N}$	$15.6/\sqrt{N}$	$26.4/\sqrt{N}$
σ_b (E_{cal} variable)	$7.7/\sqrt{N}$	$10.3/\sqrt{N}$	$16.3/\sqrt{N}$	$27.7/\sqrt{N}$

Statistical Sensitivity to b in Nab

Additional improvements in detector calibration, timing, etc.

Thanks for Coming!